AGARD-CP-593

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 593

Advances in Flight Testing

(les Avancées dans le domaine des essais en vol)

Copies of papers presented at the Flight Vehicle Integration Panel Symposium held in Lisbon, Portugal, 23-26 September 1996.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors.

Printed on recycled paper

Published December 1997

ISBN 92-836-0050-9

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Advances in Flight Testing

(AGARD CP-593)

Executive Summary

The Flight Vehicle Integration Panel, formerly the Flight Mechanics Panel, has a long history of supporting the widest dissemination of state of the art technologies and techniques relevant to the field of Flight Testing. This symposium's objective was to continue in that tradition. The symposium met its objective. Different parts of this Conference Proceedings should be valuable to anyone currently involved in the field of flight testing. Sessions dealt with the following topics:

- Systems Evaluation
- Technology Improvements
- Test Programme Overviews - to include the Airbus Beluga, the OPHER, the Rafale, the EH101, and an update on the Tornado Integrated Avionics Research Aircraft.
- Flight Techniques
- Test Management

This symposium provided an excellent forum for the exchange of the most up-to-date information on flight test. As flight test centers throughout the NATO Nations continue to be downsized and consolidated, it will become even more crucial to share recent flight test experiences in order to enhance the efficiency, cost-effectiveness, and overall quality of flight testing throughout the Alliance. The knowledge gained and exchanged at this symposium should assist the attendees in helping to provide NATO with the flight testing capabilities it will need to maintain the finest air forces in the world.

Les avancées dans le domaine des essais en vol

(AGARD CP-593)

Synthèse

Le Panel Conception intégrée des véhicules aérospatiaux de l'AGARD, anciennement le Panel de la mécanique du vol, hérite d'une longue tradition de dissémination des technologies et techniques de pointe dans le domaine des essais en vol. Ce symposium a eu pour objectif de maintenir cette tradition. Cet objectif a été atteint. Ce compte rendu de conférence intéressera donc tous ceux qui travaillent dans le domaine des essais en vol. Les différentes sessions ont porté sur les sujets suivants:

- l'évaluation des systèmes
- les progrès technologiques
- les bilans des programmes d'essais de l'Airbus Beluga, de l'OPHER, du Rafale, de l'EH 101 et de l'avion expérimental TORNADO à électronique intégrée
- les techniques de pilotage
- la gestion des essais

Ce symposium a fourni un excellent forum pour l'échange des dernières informations sur les essais en vol. Au fur et à mesure de la réduction et de la consolidation des centres d'essais en vol dans les pays de l'OTAN, il importera de plus en plus de partager l'expérience des derniers essais en vol afin d'améliorer leur efficacité, leur rentabilité et leur qualité générale au sein de l'Alliance. Les connaissances acquises et échangées lors de ce symposium devraient permettre aux participants de fournir à l'OTAN les installations d'essais dont elle aura besoin pour maintenir au niveau opérationnel optimal les meilleures forces aériennes du monde.

Contents

Theme

The major development and test challenge common to most current and future aircraft is avionics/software subsystem development and integration. New systems and applications include programmable signal processor radars, integrated flight, fire, and propulsion control systems, thrust vectoring, low observable technologies, multifunction pilot displays, multisensor integration, and other onboard software intensive systems. Acquisition and processing of large quantities of avionics multiplex data are challenges that must be met. Use of video for data acquisition and analysis is now coming into its own. There is a need for greater use of simulators, hardware-in-the-loop and integrated system ground test facilities to accelerate the integration and checkout of software-intensive systems and to improve flight test cost effectiveness of aircraft and aircraft/weapon/missile integration. Improved flight test safety through the application of advanced technologies and lessons learned should be shared. Electronic warfare systems testing will place even greater demands on the use of computer models, simulations, and other indoor test facilities to minimize flight test hours. These topics offer enough new material for an exciting symposium on flight testing.

Thème

Pour la majorité des aéronefs actuels et futurs, le défi majeur à relever, tant pour le développement que pour les essais, réside dans le développement et l'intégration des sous-systèmes avionique/logiciels. Les nouveaux systèmes et applications comprennent les radars à traitement de signal, les systèmes intégrés de pilotage, de conduite de tir et de commande de propulsion, l'orientation de la poussée, les technologies de la furtivité, les visuels pilote multifonction, l'intégration multisenseur et d'autres systèmes aéroportés exigeant beaucoup de logiciel. L'acquisition et le traitement de gros volumes de données avioniques multiplexées sont des défis à relever. L'utilisation du vidéo pour l'acquisition et l'analyse des données est de plus en plus courant. Il est nécessaire d'avoir de plus en plus recours aux simulateurs, au matériel "dans la boucle" et aux moyens d'essais au sol à systèmes intégrés, afin d'accélérer l'intégration et la mise au point des systèmes exigeant beaucoup de logiciel, et, enfin, d'améliorer la rentabilité des essais en vol et de l'intégration avion/armes/missiles. Les améliorations obtenues dans la sécurité des essais en vol et les enseignements tirés doivent être mis à la disposition de tous. Les essais des systèmes de guerre électronique feront de plus en plus appel à la modélisation informatique, à la simulation et à d'autres moyens d'essais au sol afin de réduire au minimum les heures d'essais en vol. Ces questions doivent fournir suffisamment d'éléments nouveaux pour permettre l'organisation d'un symposium fort intéressant.

Flight Vehicle Integration Panel

Chairman: Dipl.-Ing. H. WÜNNENBERG
Manager of Flight Physics & Predesign
DORNIER Luftfahrt GmbH
P.O. Box 1103
D-82230 Wessling
Germany

Deputy Chairman: Mr. B. TOMLINSON
Technology Leader
Flight Management & Control Dept.
Defence Evaluation & Research Agency
DERA
Bedford MK41 6AE
United Kingdom

TECHNICAL PROGRAMME COMMITTEE

Mr Charles VAN NORMAN
Senior Technical Advisor
412 TW/CA
195 E. Popson Avenue
Edwards AFB
CA 93524-6843
USA

Mr Jacques TRESSET
Chef du Service des Méthodes et Moyens d'Essais
Centre d'Essais en Vol
Base d'Essais de Brétigny
BP2
91228 Brétigny sur Orge
FRANCE

HOST NATION COORDINATOR

Prof. Luis M.B. da Costa CAMPOS
Instituto Superior Tecnico
Torre-60 Piso
Avenida Rovisco Pais
1096 Lisboa Codex
Portugal

PANEL EXECUTIVE

John B. WHEATLEY, LTC, USA

Mail from Europe:
LTC J.B. WHEATLEY
AGARD-OTAN/FVP
7, rue Ancelle
92200 Neuilly-sur-Seine
France

Mail from USA:
AGARD-NATO/FVP
PSC 116
APO AE 09777

Acknowledgements

The Flight Vehicle Integration Panel wishes to express its thanks to the National Authorities of Portugal for the invitation to hold this symposium in their country.

TECHNICAL EVALUATION REPORT

by

Robert A. Russell
U. S. Naval Test Pilot School
Naval Air Warfare Center Aircraft Division
Patuxent River, MD 20670
United States

1. SUMMARY

This report presents a review of the technical material presented at the sixth symposium of the Flight Vehicle Integration Panel (formerly the Flight Mechanics Panel). The intent of this report is to provide a brief evaluation of the symposium and the material presented, plus implications for the future of flight testing. But, first it is important to reflect on the history of AGARD since flight testing was initially, and continues to be, one of its important terms of reference.

2 BACKGROUND

The Advisory Group for Aerospace Research and Development (AGARD) was founded by Dr. Theodore von Karman forty four years ago in 1952. The Flight Mechanics Panel was one of the four charter panels of AGARD when formed in 1952. At that time the panel was called the Flight Test and Instrumentation Panel. The name of the panel was changed to the Flight Mechanics Panel in 1960 to reflect a substantial broadening of interests to include flight dynamics, simulation, operational aspects, design and integration, and the man-machine interface. In the spring of 1994 the AGARD panels were again restructured. The original Flight Mechanics Panel was dissolved and became the Flight Vehicle Integration Panel. In addition to Flight Mechanics Panel members, several of the members of the Guidance and Control Panel (which was discontinued) became members of the newly named Flight Vehicle Integration Panel. Again, the interests of this new panel were expanded to include integrated controls and life cycle issues.

Prior to 1960, all panel's symposia included various aspects of flight testing. After the change in panel name to the Flight Mechanics Panel and the associated broadening of technical interests, this panel has addressed flight testing in a separate symposium on an average of once every four years, reflecting continued interest throughout the NATO countries in keeping abreast of the vast progress being made in the technologies affecting the flight test discipline. This symposium is the first Flight Vehicle Integration Panel sponsored symposium considering the flight test discipline. The sharing of advances in flight test techniques, instrumentation, data analysis, and lessons learned from recent and ongoing programs results in more efficient, cost effective, and safer flight testing among the NATO countries.

AGARD symposia addressing flight testing for the past 25 years are as follows, starting with the most recent:

- FLIGHT TESTING, CP-519, Crete, Greece, May 1992

- FLIGHT TEST TECHNIQUES, CP-452, Edwards AFB, United States, October 1988
- FLIGHT TEST TECHNIQUES, CP-373, Lisbon, Portugal, April 1984
- GROUND/FLIGHT TEST TECHNIQUES & CORRELATION, CP-339, Cesme, Turkey, October 1982
- SUBSYSTEM TESTING & FLIGHT TEST INSTRUMENTATION, Geilo, Norway, October 1980
- FLIGHT TEST TECHNIQUES, Porz-Wahn, Germany, October 1976
- FLIGHT/GROUND TESTING FACILITIES CORRELATION, Valloire, France, June 1975
- FLIGHT TEST TECHNIQUES, Toulouse, France, May 1971

From a historical perspective, this FVP symposium on Advances in Flight Testing appears to be timely and appropriate to review the current flight testing environment.

3. INTRODUCTION

This sixth Symposium of the AGARD Flight Vehicle Integration Panel was held in Lisbon, Portugal, 23 to 26 September 1996. The symposium was titled ADVANCES IN FLIGHT TESTING. The symposium was attended by 188 engineers and scientists from 12 of the 16 NATO countries plus observers from the Czech Republic and Poland and a co-author from Israel.

The symposium objective was to exchange information on new flight test techniques, flight test instrumentation, data analysis, and lessons learned on the application of new technology, particularly in support of improved flight test safety from past and ongoing programs. Technical exchange of current and recent past programs should enhance safety, efficiency, cost effectiveness, and timeliness of flight testing in the NATO countries.

The symposium was divided into the following six sessions in which 31 technical papers were presented:

SESSION I. SYSTEMS EVALUATION

- Weapons integration/Missile Integration
- Avionics Systems
- Night/All Weather Attack Systems
- Propulsion Systems
- Electronic Warfare
- Navigation and Flight Control
- Trainer Systems
- Simulation in Support of Flight Tests

SESSIONS II & III. TECHNOLOGY IMPROVEMENTS

- Real Time Data Processes
- Space Position Tracking
- Human Factors
- Search and Rescue Techniques
- Lessons Learned Databases
- Airborne Instrumentation Improvements
- Aircraft Modification and Prototyping

SESSION IV. TEST PROGRAMME OVERVIEWS

- Review of Major Test Programs (Past and Current)

SESSION V. FLIGHT DYNAMICS

- Digital Flight Controls
- Aeroelastic Effects and Flutter
- High Angle of Attack
- Agility
- Flight Control Systems Safety and Effectiveness
- Rotorcraft Unique Considerations
- Missile/Weapon Separation Unique Considerations

SESSION VI. TEST MANAGEMENT

- Efficiency and Cost Effectiveness
- Operational Test and Evaluation
- Optimum Mix of Flight and Ground Testing
- Software T&E--On the Ground or in the Air?
- T&E in an Austere Environment
- Future Trends

4. THE TECHNICAL PROGRAM

4.1 Keynote

Keynote Speaker: Dr. Patricia Sanders, DOD (US)

As was noted in the last Flight Test symposium in 1992, the new world order has caused a significant change in the level of defense spending across the various NATO countries. Attendant with this continued reduction is a reduction and consolidation of the flight test facilities. In order to set the stage for this symposium, the keynote speaker addressed her views on how the US Defense Department is planning to consolidate and affordably modernize its flight test facilities for the 21st century.

The external environment affecting world security has changed from a single galvanizing threat. The US forces and its allies are now being sent simultaneously to different military actions in several regions throughout the world. The variance of the collective threat has now increased over that which existed when the Soviet Union was viewed as a single threat. For the past 5-6 years, the US DOD budget has steadily declined. In view of this decline, it was noted that a one-third reduction in overall US defense spending equates to about a two-thirds reduction in procurement funding. In order to keep a flexible and responsive force structure, the US must, in the near future, ramp up its modernization of the force. Because of continual budget reductions, the DOD must also reduce infrastructure, which has already been an ongoing process through the Base Realignment and Closure (BRAC) process. Our keynote speaker also noted the vastness of the current T&E infrastructure and highlighted the plan for the US DOD T&E centers for the next century. This plan titled **VISION 21** will be the blueprint for reduction, restructuring, and revitalizing of the US DOD T&E centers. The question before the US DOD is: "How much is enough?" Our keynote speaker strongly believes that it is much better to have two or even three exceptional T&E facilities than only one, but also stated that because of defense spending cuts, having complementary facilities may not always be affordable. Project RELIANCE and the Joint Test and Training Range roadmap are approaches to reduced duplication of T&E facilities and leverage the test ranges for training usage. Restructuring of the DOD facilities implies savings by reducing labor costs. Revitalization means a higher investment rate in the remaining T&E infrastructure in order to be able to test the new and emerging technologies. Several innovative, modern test capabilities were mentioned that have already reaped significant savings by smart use of modeling and simulation and ground laboratories. In summary, the US DOD T&E infrastructure will be under close scrutiny for the next few years until it becomes an affordable capability that is more efficient and effective.

4.2 Systems Evaluations

All seven papers, originally scheduled for the Session I, Systems Evaluation session, were presented. These papers were diverse and well presented on a wide range

of topics and covered many of the topics originally outlined in the pilot paper.

Paper 1 presented an overview of the US Air Force C-17 avionics flight test program. The test plan was organized by dividing the 8,000 test points into 30 detailed test information sheets (DTIS). Test planning, conduct, and analysis used traditional and new techniques to accomplish the test missions. Test card generation and flight planning were enhanced by the use of a new program called TEST_PLAN (see paper 9). Safety planning was of paramount importance with each new test requiring the identification of risks, a completed test hazard analysis, and risk minimization procedures. Most of the lessons learned relate to the test program, test management, effective use of simulators to reduce the flight time, and learning to use the advanced test tools to ease the test planning workload. The authors feel that the overall C-17 program has been successful, fielding one of the most advanced military airlift aircraft in the world while reducing the flight crew from four to two.

A new method for the guidance of aircraft to perform multi-target flight tests was the subject of **paper 2**. These flight test experiments addressed various approaches to autonomous guidance, from the most elaborate to the simplest approach. Various heads-up, head-down, classical localizer director, and audio channel director were considered for implementation. Flight testing, to the date of the presentation, had begun to verify the lateral control coefficients.

Through a support program, AGARD provided the impetus for an instrumented test aircraft in Portugal. The use of that instrumented aircraft for flight experiments is the subject of **paper 3**. This paper describes experiments with a 4-dimensional approach and landing system using the CASA 212 Aviocar aircraft within simulated traffic (modeling the Lisbon international airport environment) to provide a realistic traffic picture to the controllers and to display it on already accepted controller work stations. The problem being considered is the speed differences among different aircraft attempting to land in the same runway/air traffic environment. Conclusions drawn relate to the usefulness of having a real aircraft in the experiment with the other traffic simulated.

Paper 4 is the first of two papers presenting test results of precision guided munitions testing. This well organized paper presents a comprehensive summary of the ground and flight test results of a standoff, precision guided munitions with an improved IR seeker and the methods used to quantify the system performance. Flight test results included one live launch. Weapons compatibility was demonstrated with two US Air Force fighter aircraft.

Paper 5 is the first of six papers addressing unique or novel approaches to the use of the Global Positioning System (GPS) for flight tests or flight experiments. This interesting German paper presents the analysis and results of using differential GPS techniques to perform precision approaches to an airport buried in the Alps of Switzerland. The paper describes several technical approaches to reduce the errors inherent in the GPS approach and several approaches to integrity monitoring. Results of the flight testing revalidated that interference and terrain masking effects are detrimental to the precision of any RF navigation system. The paper further projects the use of self supporting inertial navigation information as a viable solution when one has to work in a severe RF environment.

Paper 6 is the first of several papers concerning the Eurofighter 2000. The Eurofighter 2000 is being built by companies in four participating nations, United Kingdom, Italy, Germany, and Spain. Alenia in Italy has the tasking for the propulsion system development and flight testing. This well organized Italian paper describes the propulsion system testing methodology and EJ200 test results. Flight test philosophy, engine flight test approach, including relight, test organization, test methods, flight test instrumentation, data analysis, data management, and early test results were discussed. Early test results indicated no surprises. Engine response, behavior, and integration was satisfactorily achieved. The use of real time analysis provided for a more efficient testing process and aided in quickly clearing the envelope.

Paper 7 presents the qualification approach for the Rafale engine (M88-2). The inflight qualification method consists of testing a representative worst case engine and verifying that it exhibits safe behavior during the entire flight regime. The paper presents a description of the engine and results of the flight tests using two Rafale airplanes.

4.3 Technology Improvements

The Technology Improvements papers were split into Part 1 and Part 2 because of the large number of technology improvements papers. Twelve diverse papers were presented in Sessions I and II covering the broad topic of Technology Improvements.

Integrated and distributed digital computers provide computational capability for every aspect of aircraft systems from the radar/mission avionics to the fuel controls/flight control systems. The topic of service release for "safety critical" software is presented in **paper 8**. This intellectually challenging paper presents a description of the United Kingdom process for service release of safety critical software. The paper considers what is required to recommend release of aircraft into service when flight safety is dependent on the correct operation of software. A general description of release to service is derived along with a discussion of testing, testing roles, contributions, and the limitations of testing.

Paper 9 presents an automated test planning system. This software, titled TEST_PLAN, is a commercially available flight test planning package for UNIX and VMS based workstation computers that allows flight test engineers to plan and track flight test program by mapping requirements to test points, flights, and flight test maneuvers. This package was successfully used on the USAF C-17 flight test program to help in planning the flight test program and used in preparing flight cards and certain reports. This automated aid to test planning appears to be beneficial for large, sophisticated flight test programs providing efficient generation of information with reduced engineering effort.

Paper 10 is the second of two papers presenting test results of precision guided munitions testing. The focus of this paper was the reduction of aircrew workload with the introduction of an inertial navigation system that is GPS position and velocity aided. Flight test results are presented validating the improvements afforded by the INS/GPS during the mid-course guidance phase.

Paper 11 is the first paper describing helicopter testing. This paper describes the emerging technologies being

considered for the acquisition of the UK Apache helicopter (Longbow version). In particular, a Defensive Aids Suite (DAS), Helmet Mounted Displays (HMD), improvements in sensors and information management, ideas on a future handling qualities assessment, and increased use of simulation for clearance testing are some considerations for the UK Apache. The author further envisions that the ADS-33 specification will become widely accepted as the definitive standard for future helicopter flying qualities evaluations.

The design requirements for a data acquisition system for the Royal Netherlands Air Force F-16 Mid-Life Upgrade programme is the subject of **paper 12**. The paper presents the starting point requirements for the new data acquisition system reflecting on the existing F-16 instrumentation system. A general concept to meet functional and operational requirements is described. Strong consideration is being given to the US DOD Common Airborne Instrumentation System (CAIS). However, some technical problems and schedule/cost problems will likely dictate the selection or non-selection of CAIS to fulfill this requirement.

An intriguing discussion of the use of modeling and simulation to reduce flight testing is provided in **paper 13**. The paper examines the entire aircraft development process, reveals the impetus behind the initiative to reduce flight testing, and provides successful and unsuccessful examples of reliance on modeling and simulation. Five reasons are given that are used by the budgeteers as a basis to reduce flight testing: It costs too much; it takes too long; it attracts high-level scrutiny; it reveals too many design deficiencies, some of which are of arguable significance; and program direction tends to shift to large and domineering test organizations. The author argues that the principle action to correct the perceived problems with flight testing is not necessarily a reduction in flight testing but better leadership. The point is made that a large reduction in flight testing cannot be simply mandated without introducing unacceptable risk. The risk lies in the increased likelihood of producing and fielding weapon systems which simply do not perform adequately and which present hazards to the operator. The best balance of modeling and simulation and flight testing in aircraft development is determined by the perceived reliability of the predictions, the requirements of a logically planned and safe flight test program, and the need to address deficiencies uncovered during the testing. Several pages of tabulation are included showing "unanticipated characteristics" discovered during flight testing. This paper provides an excellent dissertation on the value added from "flight testing".

Another interesting use of Differential GPS (DGPS) is the subject of **paper 14**. This paper describes a program using a Falcon 20 research aircraft to investigate the use of DGPS for aircraft guidance on precision instrument approaches and to measure aircraft performance parameters during typical flight test maneuvers needed for aircraft certification. The initial DGPS configuration using the Nov Atel 951R receivers on the aircraft produced unacceptable vertical measurement errors largely due to multipath. An upgrade to a Nov Atel RT-20 differential GPS improved height accuracies to within 20 centimeters, well within the accuracies required for Category I approaches. This configuration was used successfully to measure aircraft landing distances under various James Brake Indices (JBI) from a height of 50 feet (15 meters) to a complete stop.

Paper 15 presents a most interesting study of computer generated synthetic vision providing the means for guidance in poor visibility conditions. The approach presented is based on synthetic vision generated by a computer and on precision navigation provided by satellite navigation. The high precision of navigation performance is achieved with an integrated DGPS/INS system which couples differential satellite and inertial sensor data. The computer makes use of a stored database containing all relevant information of the terrain and its elevation as well as of buildings, obstacles, etc. A flight test program was executed to cover a wide range of synthetic vision guidance applications. Four test series at different geographic areas were conducted. The flight test program results show that the synthetic vision enables the pilot to precisely control the aircraft and successfully perform the flight tasks. The tests demonstrated that this advanced guidance concept worked effectively for poor visibility flight conditions. The 3-dimensional image of the outside world and the integrated guidance symbology featuring the innovative tunnel display provided positive results.

Another creative use of the significant accuracies provided by differential GPS is presented in **paper 16**. This paper describes the validation of a technique for the simultaneous determination of pitot static position error and the calibration curves for AOA and sideslip sensors for helicopters. The differential mode of the GPS was used to obtain accurate measures of aircraft position and ground speed. The aircraft was flown in a windbox pattern while recording standard flight test parameters. The results demonstrated that accurate calibrations could be obtained with reduced flight time and cost over conventional calibration techniques when flying within specific constraints outlined in the paper. Also, the best results were achieved with calm winds. One problem, unique to the helicopter, is that the rotor blades momentarily blank the satellites, which lowers the signal-to-noise level of the satellite signals.

An attempt to increase the directional stability of an F-16 aircraft at all angles of attack into the post-stall regime is the topic of **paper 17**. Wind tunnel testing had shown beneficial effects of forebody chines. Flight tests were conducted with and without chines as an adjunct to the program investigating thrust vectoring to very high angles of attack. The flight test results showed an apparent significant effect of the forebody chines on pitching moment while the chines effect on lateral/directional characteristics were mixed. The limited dynamic maneuver data showed that the chined forebody was less directionally stable than the baseline F-16, contradicting the 30 deg wind tunnel data. This paper shows some interesting results, although inconclusive, but most likely leading to additional wind tunnel and flight testing at high AOAs.

Paper 18 describes the development and use of telemetry and in-flight analysis for flight trials at BAe Warton plus the current status of in-flight aerodynamic analysis techniques for Eurofighter 2000. The paper gives a brief, but enlightening, history of the development and use of telemetry and philosophically how it was and is used in support of flight testing. The Real Time Analysis (RTA) approach, developed by BAe Warton in the 1980's, was used exclusively for the EF2000 stability and control and loads flight development and now is in use for aerodynamic envelope expansion trials. Even though the flutter clearance approach involves upfront increased manpower, the overall method used on EF2000 has

proven to be cost effective reducing the number of required flights.

Paper 19 describes some innovative application of the world wide web to the distribution of flight test data and the management of financial data associated with flight test data processing. The paper describes the evolutionary history of Information Technology from relational database management to object-oriented methods. The authors explore the WWW as a transformational force in redefining the flight testing business. By using the client server architecture and the WWW technology described, a functional post flight data processing workflow system was created. This system has three key benefits as defined in the paper.

4.4 Test Program Overviews

Session IV on Test Program Overviews provided five papers covering a broad range of programs from the European NATO countries.

Paper 20 presents the flight testing and flight certification program for the Airbus A300 600ST Super Transporter Beluga. The Beluga was built by Aerospatiale to replace the "Super Guppy". This larger size and different shape of the Beluga fuselage required a full range of flying qualities and handling qualities testing. Because of the large fuselage cross-section, the c.g. moving in the vertical plane had to also be monitored. The flight certification program was completed in 330 flights with handling qualities better than predicted. Airbus has orders to manufacture four Belugas.

In **paper 21** the successful testing and analytical work that led to the certification of the OPHER smart munitions on the AMX aircraft for the Italian Air Force is described. The OPHER system is an autonomous precision strike smart munitions for day and night air-to-surface attack of tanks and various types of vehicular and marine targets. Once released from an aircraft toward a target area, the OPHER autonomously selects the target and guides itself until a hit is achieved. The paper presents a good description of the weapon, the certification testing, and provides graphs of the test data.

A look at the past five years of Rafale testing is presented in **paper 22**. The author presents a good overview of significant testing including integrated systems development, some worthwhile lessons learned from the program, and a perspective of how effective the test organization performed. It was stressed that the government organizations had an active and early role in the program.

Paper 23 describes the EH101 helicopter flight development programme from initial conception to the present day. The paper presents lessons learned during the flight test phase and discusses significant milestones achieved. The helicopter was developed to fulfill a replacement need of the Royal Navy and the Italian Navy. Nine platforms were used in the development and testing phase. There were three core variants developed to meet the various operational needs. Testing was performed at a single site. The EH101 integrated development program is planned to be completed by the end of 1996. The first production aircraft is now flying. Installed engine and structural loads survey data gathering is continuing as part of the production standard qualification process. Other trials are continuing to integrate a dipping sonar for the Royal Navy.

Paper 24 describes the major features, the flight trials, and the role of the Tornado Integrated Avionics Research Aircraft (TIARA) operated by DERA, Farnborough, UK. The particular TIARA aircraft described in the paper was heavily modified to provide for the evaluation of IR sensors and helmet mounted displays. A future installation of the Blue Vixen AI radar will complete the suite of equipment and allow trials on sensor data fusion. The paper goes on to describe how this suite of sensor hardware will be used for various trials.

4.5 Flight Dynamics

In session V three papers are given on the topic of flight dynamics.

Paper 25 presents the investigation techniques for handling qualities and aerodynamic characteristics of the Eurofighter 2000. The paper emphasizes analysis methods for flight, mechanical, and aerodynamic evaluations suitable for a very agile, highly unstable fighter aircraft. Various analysis methods in the time domain and frequency domain such as Z-transformation and Fourier analysis methods for system stability evaluations are presented with representative test results. The analysis approach at DASA is a mixture of on-line monitoring and analysis while the aircraft is airborne and detailed off line analysis post-flight.

In **paper 26** flight testing of the flight control laws for an electronic flight control system of a small transport aircraft (100 seater) are presented. In a cooperative effort between German industry and the German government, the flight control functions were tested on DLR's test bed aircraft Advanced Technologies Testing Aircraft System (ATTAS) using the ATTAS experimental fly-by-wire system. The paper provides an overview of the flight control law development and testing within the small airliner flight control law investigation and refinement (SAFIR). Design objectives for the 100 seater are reviewed, a system overview is given, the flight control law functions are briefly explained, and the development process is described. Representative flight test results are presented.

Paper 27 was canceled.

Paper 28 presents the flight tests of the Airbus A320 flight control system. No finished paper was available at the symposium, only a copy of vu-graphs presented. The majority of the paper describes the flight control system development before first flight and the various protections provided in the flight control system. Flight tests included specification validation, correction and update of previous implementation choices, certification, and validation with the customer. An iterative process was used taking flight test results to update the computer models, make necessary changes, and revalidate with additional flight tests. Several vu-graphs described the on-board flight test instrumentation. Representative time histories of the protection modes are presented.

Paper 29 is the first of two papers on the X-31A Enhanced Fighter Maneuverability program. This paper presents the evaluation of the high Angle-of-Attack handling qualities for the X-31A using Standard Evaluation Maneuvers (STEMs). The emphasis of the testing is for AOA between 30 and 70 deg. The test results show longitudinal gross acquisition handling qualities as borderline level1/level2 performance and lateral gross-acquisition handling qualities at level1/level2 below 45 deg AOA, degrading to level 3 as AOA increases. The fine tracking performance in both

longitudinal and lateral axes also are rated level 1 near 30 deg AOA, with the ratings tending to level 3 as AOA becomes larger than 50 deg. All of these ratings don't match the expectations from the extensive close in combat testing where the X-31A demonstrated fair to good handling qualities for high AOAs. This paper presents the test results for high AOA, a discussion of the preparation for the maneuvers, the pilot ratings, and evaluation of the results made in conjunction with existing Neal-Smith, bandwidth, Smith-Geddes, and military specifications. This X-31 paper is very comprehensive, presenting solid data that is well supported with a comprehensive analysis. This paper was a good lead-in to the following paper on the X-31A tactical utility.

Paper 30, the second paper on the X-31, presents results of the post stall capabilities, up to 70 deg AOA , of the X-31A aircraft. The results are quite exciting in that they show that the X-31A, using post stall technologies, including a thrust vectoring system, was significantly superior in close-in-combat (CIC) to existing state of the art fighter aircraft. Improvements approached an order of magnitude. The tactical utility of the X-31 has been proven. The author describes several post stall maneuvers.

4.6 Test Management

Two test management papers, one from each side of the Atlantic, are presented in this session VI.

Paper 31 was canceled.

A comprehensive flight test program overview and management concept, presented in **paper 32**, is the final paper presented on the Eurofighter 2000. This paper presents an interesting management concept of how four individual flight test centers in four different European countries, UK, Italy, Germany and Spain, collaborated to conduct development testing meeting design targets within the given program structure and time schedule. This interesting paper shows how the four countries have successfully managed the program using 7 development plus 5 instrumented production aircraft and how the partner companies have progressed the aircraft from design through initial operational certification to the final standard. The author provides a comprehensive discussion of flight tests, completed and planned, and how the flight test programme is to be shared among the four participating partners.

Paper 33 presents the integrated test team (ITT) concept being utilized on the US Navy/US Marine Corps V-22 Osprey aircraft development. The paper, written from a government management perspective only, discusses the concept, development, benefits, challenges, and lessons learned associated with the establishment and operation of the V-22 Osprey ITT. The Navy's ITT is based on the combined test force (CTF) concept developed by the US Air Force. The paper presents the rationale for establishing the ITT, some of the obstacles that had to be overcome between government and industry, successes achieved with the ITT, and lessons learned.

4.7 The Role of Government in Development Flight Testing in the 21st Century

The final session was a roundtable panel of experts assembled by the Technical Program Chairmen (TPC). Those participating on the panel, in addition to the TPC, Mr. Van Norman (US) and Mr.

Tresset (FR), were: Dr. Patricia Sanders, Office of the Secretary of Defense (US), Mr. Andre Benoit, Eurocontrol (BE), IGA Herve Groualle, Commander, French Flight Test Center (CEV) (FR), Mr. Robert Hartley, Flight Test Manager, Flight Test Engineering, BAe Warton (UK), and Mr. Jacques Desmazures, Vice President, Flight Test Directorate, Dassault Aviation (FR). Prior to the panel, the TPC had given the following controversial question to each panel member for them to consider:

There has long been a debate within the acquisition community regarding responsibility for accomplishment of Developmental Test and Evaluation (DT&E) of military aircraft. Contractors maintain that DT&E is an integral part of the weapon system development process, is the contractor's tool for ensuring their product meets the customer's requirements, and thus should be accomplished by the contractor without customer interference.

The government customer's position has been that aircraft weapons systems are so costly and take so long to develop that the customer cannot wait until product delivery to determine if the weapon system meets expectations. Furthermore, many examples of failures of contractors to provide quality products have been cited and the taxpayer ends up being the victim. Thus, the customer's position has been that government conducted DT&E is required to ensure that design and manufacturing risks have been minimized, to determine contract performance, and to determine if the system is ready for operational test and evaluation.
Declining defense budgets in some NATO countries have resulted in "acquisition reform" which in a growing number of cases, includes reductions or elimination of government involvement in DT&E. Also, mergers of aerospace companies and emergence of common requirements from different nations is forcing both the government and the contractors to rethink the organization of DT&E.

In your opinion, what should be the role of the government in developmental flight testing in the 21st century?

Each of the panel participants delivered an opening statement addressing the above question. Dr. Sanders, the keynote speaker, addressed the issue as she saw from the US perspective. She spoke of acquisition reform ongoing in the US DOD, the push away from specifications to best commercial practices, and issues on investment in T&E facilities. She reflected on several statements made during her keynote address. Mr. Benoit spoke about how to improve the air traffic densities in Europe, posed whether we eventually would continue to need pilots in the aircraft as automation continues to advance, as well as the future need for air traffic controllers on the ground. He talked about further concepts of knowing the 4-d position of the aircraft and potential expanded uses of data links. Mr. Groaulle related France's experience with testing the Mirage and Rafale. He stressed the best possible integration of government testing with industry testing. Mr. Hartley, who was the most vocal panel member, reflected on his experience with the UK government historically duplicating the industry testing and stressed the integrated team approach as reflected in the EF2000 program overview paper. He further stressed the regulatory , air worthiness, and flight certification issues. He also said that the challenge is to form a successful team and that the ultimate responsibility rests firmly on industry and contractors, not the government. Mr. Desmazures stressed cost reduction as crucial and discussed the

teaming being done in the European countries. He also stated that test ranges need to be preserved.

The European panel participants stressed the teaming ongoing in the European countries. All panel participants agree that T&E/flight testing can most effectively be done as a team. Most agreed that the customer (government or commercial) should be involved early in the design, development and flight test phase to achieve a better end product.

Some challenged Mr. Hartley's statement that the contractor has ultimate responsibility. One question addressed the lack of flight safety being mentioned in any of the panel participant's statements and was specifically addressed to the European panel participants. A question addressed the oversight required by the government acquiring a military aircraft. All agreed that early involvement without duplicating the contractor testing is the most cost effective approach to achieve the best final product and minimize the acquisition time cycle. There was some discussion about various experiences with different types of contracts. Countries on both sides of the Atlantic had gone to a fixed price contract as a "knee jerk" reaction to the unbounded cost-plus contract. All agreed that the fixed price concept did not provide enough flexibility during a development program.

The questions and discussion during this panel were interesting and challenging. This author believes that the problems faced by the flight test facilities are similar on both sides of the Atlantic. The reduction in the number of new platforms being fielded and the general trend to reduction in the flight test business base will continue to bring pressure for T&E facility infrastructure reduction and consolidation. The trends, both in Europe and the US, toward teaming is growing. Integrated test teams, as highlighted by the V-22 paper 32, and the Eurofighter teaming across four European nations, paper 33, are making for more efficient and cost effective flight testing. The teaming appears to be a "common-sense" approach to consciously spread the flight test work between industry and government and across industries in different countries thereby keeping a reasonable level of flight test expertise productively employed. In short, the teaming is the best way for the flight test community to survive in these austere times.

5. CONCLUSIONS

The 6th Symposium of the Flight Vehicle Integration Panel is considered by this author to have been an unqualified success. The goal of this symposium was to disseminate the most recent information on flight testing techniques, instrumentation, data analysis, and recent flight test experiences. That goal was achieved to a great extent because of the high quality of papers, quality of presentations, good visual aids used during the presentations, and the selection by the Technical Program Committee of the most relevant flight test information available in the mid 1990's. The availability of all preprints of the 31 technical papers (two of which were copies of the vu-graphs only) at the meeting was most welcome and helpful in following the presentations as well as generating relevant questions. Throughout the symposium there were in excess of 100 attendees each day of the symposium in spite of many other on-going committee and working group meetings.

6. RECOMMENDATIONS

That the Flight Vehicle Integration Panel continue the recent 20-plus year tradition of holding a flight test symposium every 4-5 years to share recent flight test technologies, test techniques, recent programs, and lessons learned. As the flight test centers continue to be reduced, downsized, and consolidated, it becomes even more crucial to share recent flight test experiences to help improve efficiency, cost effectiveness, and the quality of flight testing.

Keynote Speech

A Small Country's Contribution for the Development of Aerospace Science, Technology and Production

by Abílio Cruz Júnior
Admiral (Ret.), PO Navy

Distinguished Chairmen,

I started my career in the Navy as an aviation-pilot way back in the year of 1950 and although my permanence in naval aviation only lasted a few years, the flight experience and its technological needs left a deep and lasting impression in my mind.

Curiously, since I retired, ten years ago, I became more and more involved in defence related research and I also developed an increasing interest in aeronautics and space matters.

My contact with the Portuguese Defence Industries and more recently the co-ordination of the Portuguese National Program for Space Science and Technology gave me a broader view of the problems and potentialities of the aerospace field for a small country like Portugal.

This is the experience that allows me to present to you in a simple and straightforward manner the point of view of a small country on what its contribution may be for the development of aerospace science, technology and production.

Let me also mention that at the end of 1994 and beginning of 1995 I was a member of the Nato High Level Review Board which examined Nato's scientific structure and recommended a new upper-level management model, maintaining the AGARD "modus operandi" which has obtained excellent results.

Returning to the subject:

Like many others in the western world, Portuguese people developed an early passion for air adventure as they had done in the past for the sea. A few pioneer air trips mark that initial period. Among them stands out the crossing of the South Atlantic Ocean between Lisbon and Rio de Janeiro, by Sacadura Cabral and Gago Coutinho, in 1922.

In the first decades of Aviation in Portugal there were small military fleets with their own means of maintenance and no industrial production.

The Second World War with the beginning of regular air transportation and the constitution of our still existing national airline, TAP, or Air Portugal, and on the other hand the creation and development of the Portuguese Air Force, originated two aeronautical industrial poles of certain importance: a civilian one, at TAP, and a military one, OGMA, both dedicated essentially to aircraft maintenance and repairs, and some production in the area of aircraft structure components having been developed in OGMA. This industrial development required the participation of aeronautical engineers, many of them having graduated from foreign Universities.

In the early nineties, a new era in the aerospace field began in Portugal as a result of the building-up of a scientific community which permitted our country's participation in various European programs in this area.

In what concerns AGARD the Portuguese Air Force should be credited with the fact that Portugal has had such an active and interested participation in its panels, both through its engineers and those from the University community, with whom it has always co-operated in a worthy and profitable way.

People felt then the need to regard the aerospace field in an integrated way and different initiatives took place which had great importance for our country.

First, in the area of college education two university courses were created, one in Aeronautical Engineering at the University of Beira Interior, and the other in Aerospace Engineering at the Technical University of Lisbon. The first graduates will join the work force this year, and it is anticipated that by the year 2000 Portugal will have about 100 new graduates. They will form the critical mass necessary for laboratory research and for industry.

The second initiative has to do with the elaboration of a National Program for Space Science and Technology and with the creation by the Government of an Interdepartmental Structure responsible for the co-ordination of that Program.

In 1994 I was appointed by the Government as Co-ordinator of this Structure and my mandate ended just last week.

This Structure defined a national strategy for the aerospace area based upon the following points:

- Use and development of the technological and industrial base in the aeronautical field;
- Negotiation of a Co-operation Agreement with the European Space Agency (ESA), and starting participation in its programs;
- Involvement and active participation in the space activities of WEU and NATO.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

This mobilisation made it possible to conclude in July 1996 the Co-operation Agreement with ESA and prepare national industry for participation in European aeronautical programs.

In this way Portugal is taking decisive steps towards integrating the European development process and contributing with its know-how and its human resources in a complementary way to the European common objectives.

In 1991 an initiative took place which resulted in the production of a micro-satellite for testing and research purposes. The University of Surrey, INETI, OGMA, EFACEC and MARCONI participated in this initiative. This satellite weighs about 40 kilograms and it has two low resolution cameras for earth observation. It ensures some communications in the "store and forward" system and allows certain scientific experiments in the Astrophysics field to be carried out. It is designated POSAT-1 and it was launched in late September 1993.

The consortium that was formed for this purpose intends to prepare the launching of new satellites and even the constitution of a LEO constellation with the purpose of ensuring a regular telecommunications service. This initiative is causing strong controversy due to the high level of investment that is necessary and to the risk involved. For these reasons the Government hasn't taken a decision on the subject yet.

I would like to conclude by characterising the present situation in Portugal in the aerospace area. We have:

- A well developed scientific community with strong international integration;
- An industry with regular presence in the field of aeronautical maintenance and repair, but with little expression in the area of aerospace construction and production;
- An expanding internal market of the Armed Forces and aeronautical operators;
- Political will for integration in European systems.

Finally let me thank the Chairmen of the Program Committee for this Symposium, Mr. Van Norman and Mr. Tresset, for the honour and the opportunity of speaking of my personal experience and trying to convey it to such a distinguished assembly.

Please accept my best wishes for the success of your work.

Thank you.

Lisbon, 23 September 1996

"Consolidation and the Future of Flight Test Facilities"

Keynote Address of
The Deputy Director, Test Facilities and Resources
Dr. Patricia Sanders

to the
Advisory Group for Aerospace Research and Development
Flight Vehicle Integration Panel Symposium on
Advances in Flight Testing

23 September 1996

Ladies and gentlemen, professional colleagues, it is an honor and my great pleasure to be with you and share some of my views on where the U.S. Department of Defense is headed to consolidate and affordably modernize its flight test facilities for the coming century.

Since that fateful day nearly a century ago when Wilbur and Orville Wright left their bicycle shop to achieve the long-sought dream of heavier-than-air flight, humankind has indeed come a very long way technologically—and much of that progress can be traced to the aerospace era that began with the Wright Brothers. In less than a century we have progressed from that first highly tenuous flight test at Kitty Hawk to the point where each day in the U.S. alone the equivalent of the population the city of San Diego climbs aboard commercial airliners and travels safely to their destinations.

The success of the Wright Brothers helped spur other seemingly outlandish theories, such as those of Robert Goddard, whose early rocket experiments in a cabbage patch in Massachusetts gave way exactly a century later to Neil Armstrong and Buzz Aldrin landing on the moon.

As an indication of how far, fast, and high aerospace has progressed, the entire first flight of the Wright Brothers could have taken place inside the huge external tank that today serves as the structural backbone for the Space Shuttle. Similarly, Goddard's most famous rocket reached an altitude about half as high as the Apollo launch vehicle—while the latter was still sitting on the pad.

To some extent we are now paying the price for our past successes. There are those who ask why we should build new airplanes when the ones we already have carry passengers to many of their destinations in less time than it takes to travel to and from the airport and await one's baggage. During the Cold War era many in the U.S. argued that the nation shouldn't buy the equipment our industry was producing because it wouldn't work. Today, on the heels of the Persian Gulf experience, these same people proclaim the

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

nation shouldn't buy the equipment our industry is producing because it works so well that we don't need any more of it.

As I look broadly at the external environment that impacts our national security, I note that so many things have changed—not just in the past 20 years, but in the last year or two. In the post-Cold War world, we no longer face a single galvanizing threat such as the former Soviet Union. Instead there is increased likelihood of our forces being committed to limited regional military actions—coalition operation—in which our allies are important partners.

I would sum up our current national security environment in statistical terms by saying the mean value of our single greatest threat is considerably reduced. But the irony of the situation is that the variance of the collective threat that we deal with, plan for, and must counter is up.

This gives us some pause in trying to plan intelligently. In response to reduced mean value of the threat, the United States has cut end strength by about a third from 1985 levels. But at the same time, the increase in variance has caused deployments of U.S. forces to go up by a third—a fact that I am sure you are well aware of.

In fact, most informed observers realize that the overall U.S. defense budget has been cut by about a third in real dollars since its peak in the late 1980s. But what most don't grasp is that for every percentage point that the overall DoD budget changes, either up or down, the procurement budget invariably changes by two percentage points. Thus procurement funding is down by about two-thirds—actually 72 percent. Procurement has traditionally been the most volatile component of the budget in a draw down because it is not necessary to purchase new equipment for a smaller force structure.

But consider for a moment how such reductions impact the ultimate user of the equipment procured: the soldier, sailor, airman, or marine. One can readily calculate –by dividing the value of all the tangible assets the department owns, excluding land and buildings, by the annual reinvestment in those same assets—that the average item of military equipment in America's inventory will have to last 54 years. This in a world where technology generally has a half-life of anywhere from two to ten years and casualties in combat are heavily dependent on the quality of technology involved in the battle—as both sides vividly learned during the war in the Persian Gulf. Mindful of the aging equipment upon which our armed forces increasingly must depend, General Ron Fogleman, the Air Force Chief of Staff, this last year testified before Congress that, "We are living off the procurement of the past. It has to stop."

Because this approach defers long term modernization and future readiness, we view this as a temporary condition. The planned draw down is nearly complete with the FY96 budget, and so, from FY97 on, we will have to increase our spending to sustain modernization of the force. We have to start a ramp-up in modernization. And we have

to have a modernization plan that will focus on building a ready, flexible, responsive force for the changing security environment in which we live.

But I must be candid with you. We are making three critical assumptions about where we will get the money to make this work. The first big assumption in our defense planning is that the defense budget modernization line will stop declining and begin to go back up. This will depend ultimately on actions taken by the DoD and the Congresses two and three years from now. I am not confident that the projected increases we are counting on will be there in 2001. The difference in budget authority set by the Congressional Budget Resolution with that of the programmed budget shows an unsustainable ramp in the near term…and in the long term…It is a sobering state of affairs. But my concern is not directed only at the Congress. The DoD itself must continue to reduce infrastructure and to execute plans to achieve greater efficiency if we are to keep the rug from being pulled out from under our modernization plans.

This leads me to the second basic assumption in the Department's planning—that we will achieve significant savings by closing bases. As I said earlier, the DoD budget and force structure are both down about a third from their peak levels in 1985. Guess what? Our infrastructure is only down by 18%. It is the reason why the Base Realignment and Closure (BRAC) programs have been so important. The program we have laid out through BRAC 95 will reduce the infrastructure by an additional 11% over the next few years. It is important to bring this infrastructure into balance with our smaller force structure…the savings produced are needed to plow back into our investment program.

The third big assumption in our defense planning is that we will get significant savings by overhauling our defense acquisition system. The idea here is to be more efficient in what we buy; how we buy it; and how we oversee the buying process. As we look at the defense acquisition system in detail, what we find is that the system is not broken—it fields equipment that is second to none in the world. What we find is that the system can and must operate more efficiently.

Our flight test capabilities and resources are key players in this challenge to modernize our forces. In the U.S., most of our flight test facilities are a part of the Major Range and Test Facility Base (MRTFB), a national asset comprised of the 21 principal T&E centers, including ranges. It includes 21,00 square miles of land –about 55% of the Department's land assets, 243,000 square miles of water surface, and 221,000 square miles of airspace. It represents a $30 billion investment and at its peak in FY91 employed over 55,000 military, government civilians, and contractor personnel—now closer to 45,000. The facilities themselves are part of the infrastructure we need to consolidate and make more efficient. The capabilities they provide represent one of the areas in which we have the potential to more affordably acquire the needed weapon systems.

In light of the circumstances in which we find ourselves, the question confronting the flight test community is "Now what do we do?" The first most obvious choice—and to some the favorite choice—is to do nothing: hunker down, and hope that with a little

more time things would get better. This strategy is founded—or more accurately foundered—on the suggestion of John Lowenstein of the Baltimore Orioles, who when asked what could be done to improve the game of baseball, answered, "They should move first base back a step to eliminate all those close plays." Hoping that somehow, someone would move the bases back to give a little breathing room simply isn't going to happen. Our problems are more profound and all things considered, history has not been kind to those who have followed the "stay the course" approach when faced with profound shifts. Emblazoned in this hall of fame are such names as American Motors, Pan Am, Penn Square, Wheeling Pitt, and a host of others. If our flight test profession is to remain a quality, competent, and capable resource we cannot simply wait for the current crisis to pass. As a colleague of mine says, "Hope is not a strategy."

If the answer is not to do nothing, the canonical solution proposed by many politicians, academics, and media after every downturn seems to be to diversity. The aerospace industry itself has certainly tried this before. In spades. Examples of the things the industry has demonstrated it cannot produce at a profit include guitars, buses, monorails, pagers, solar energy systems, oil skimmers, modular housing, and a host of other ill-considered pursuits. In fact, the industry will tell you that its record at diversification is largely unblemished by success. Theirs a textbook case of failing to understand their core competencies.

Likewise these days one is likely to find all varieties of "innovative" endeavors being pursued on our test ranges in an effort to preserve and more fully utilize our infrastructure—some more or less aligned with our profession. It is not unusual to find race cars, motorcycles, even skiers in our wind tunnels. We employ our radar systems to monitor our borders in support of the war on drugs. And one of our test ranges is actually in the geothermal power business! And while we have for the most part succeeded in these endeavors, there has by and large been only marginal value added in these areas. Lest I be misunderstood, diversification is important—and can be accomplished successfully and profitably—but it has to be pursued very deliberately over a period of time. The fundamental problem is that Washington can cut the defense budgets faster than we can create new jobs and revenue through diversification.

But if doing nothing is not the solution—and if doing something different is not the solution—what then is the solution? It may seem that we have encountered the situation once described by Woody Allen in the following terms: "More than any other time in history, we face a crossroads. One path leads to despair and utter hopelessness. The other, to total extinction. Let us pray that we have the wisdom to choose correctly." If we desire to proceed, perhaps we should turn to a higher order of collective wisdom—namely the timeless counsel of that great American philosopher, Yogi Berra. Mr. Berra advises, "When you come to a fork in the road, take it." And he is quite correct: Some reasonable, decisive action is almost certainly better than no action at all. The preferred solution thus becomes one of doing that which we already have learned to do so well—but to become increasingly efficient at it through consolidation and proactive planning for the future.

Our DoD is preparing such a decisive plan for its test and evaluation centers for the twenty first century. This plan, entitled Vision 21, will serve as our blueprint by outlining the process that will enable DoD T&E centers to meet the needs of the warfighter, both now and in the future, despite a changing threat environment and reduced budgets. Vision 21 will rest on three pillars: reduction, restructuring, and revitalization.

- **Reduction** of current infrastructure costs with particular emphasis on the elimination of old, high-maintenance, and inefficient facilities while retaining critical capabilities for the future.

- **Restructuring** to capitalize on the reengineering revolution sweeping both government and industry and offering a rare opportunity to shed many of the old constraints that reduce our productivity and efficiency.

- **Revitalization** to modernize aged T&E centers, with emphasis on technologies of the twenty first century, cross-service sharing, improved efficiencies, and reduced cost of operations and maintenance.

We view this plan as an opportunity to respond to the needs of both the U.S. forces and the nation with a positive look to the future that leaves behind the remnants of the Cold War, ensures the security of the country, and provides for the necessary modernization of our defense capabilities.

I will briefly address each of the three pillars in turn, beginning with **reduction**. There have been a number of separate initiatives that have and continue to result in reduced test infrastructure, the most important of which is the Base Realignment And Closure (BRAC) process referred to earlier. It should be noted again that the effect of these consolidations and closures has yet to be fully realized, but significant reductions in DoD infrastructure are intended to result from the four rounds of Congressionally approved base closures and realignments in fiscal years 1988, 1991, 1993, and 1995. Only the BRAC 88 decisions have been fully implemented. The BRAC91 actions are currently in process, and only a few of the BRAC 93 and BRAC 95 actions have even been started. Clearly, the most significant of the BRAC consolidations and reductions remain to be executed. And equally clearly, while we are committed to retaining our critical land, sea, and air space, we have not seen the last of our reductions in test facilities.

The bad news here is that it takes money to save money. When we close down facilities, we actually end up spending money in the near term. Typically it takes between two to three years to break even before there is a net savings in the process. But we have to succeed in our plans for closing facilities. Yet since test facilities need adequate capacity in order to provide support that is cost effective to weapons programs and the DoD as a whole. The question is how much is enough.

The plethora of consolidations has raised several profound policy questions: the principal one of which is at what point are the capabilities and resources which have been so essential in the past undermined? My answer to that question is straightforward: It is much better to have two or even three exceptional facilities than one. Unfortunately that choice is basically irrelevant since it is not among the options we have been given. Unfortunately the defense budget has been cut so deeply that even the choice of having two strong complementary facilities may not always be available. The debate about whether we would rather have ten facilities—or nine or six or three thus takes on the same connotation as arguing about the number of angels that can dance on the head of a pin.

In order to fulfill our test mission in the face of this reduced and reducing number of facilities, we have taken a number of initiatives. The military Services established the T&E Reliance Project in 1990 as a corporate and cooperative management approach to promote coordinated, centralized investment planning without inhibiting decentralized execution of testing. Under Reliance, a single manager or Lead is generally assigned responsibility for planning for DoD test capability in a specific area, e.g., electronic combat. The Lead is responsible for fostering cross-service management arrangements, identifying unwarranted duplication, and making recommendations to improve test facility management.

In 1995, National Aeronautics and Space Agency (NASA) and DoD Integrated Product Teams were formed to evaluate where consolidations, improvements in efficiencies, and cost savings could be identified and obtained between the two agencies. Particular emphasis was placed on more efficient management of technology programs and the major facilities of both agencies. The teams gathered information on major facilities used by NASA and DoD since 1993 and reviewed future workload requirements. To ensure future and continual coordination, alliances are being recommended among DoD, NASA, industry and appropriate universities. These alliances are responsible for monitoring and improving the use of facilities, reducing costs through commonality, and improving test technology by endorsing facility investments. Interagency Reliance and co-management of facilities are being considered.

On another front, an emerging sense of mutual need and interdependence is being fostered between test and training ranges. Since both test and training share certain functional requirements, ranges and range instrumentation have similar characteristics for the respective applications. The Joint Test and Training Range Roadmap describes a conceptual vision of a range structure that supports seamless, integrated operations across the physical boundaries of designated cooperatively linked test and training ranges. The vision, along with a general strategy and business plan, provide a framework for making decisions on development and acquisition of future range and instrumentation systems. The focus is on presenting a range paradigm that will lead to more effective and efficient use of the existing and projected range resources and enable mutual test and training use where required and appropriate.

Now, since growing by shrinking is a bounded strategy, the second pillar of Vision 21, **restructuring**, places the emphasis on providing more efficient and affordable testing through better planning, better processes, better business practices, and better teaming.

It is clear that the bulk of our money is spent on manpower—at least 54% for government personnel and an additional 15 percent for contractor services. This should not be surprising—it is common for most industries—but interestingly, many people outside the test and evaluation business who want to promote a pet "reinvention" scheme fail to appreciate this fact. Fundamentally, manpower is the high leverage point—if a reinvention idea does not reduce required manpower, it will not have significant impact. Closing facilities is a good example: if we reduced facility ownership costs to zero, we would save less than 5 percent of our budget. So facilities—moved, closed, or consolidated—are not a high payoff area unless the closing or moving also saves manpower.

A disciplined planning approach provides the basis for looking at how we do testing and for identifying better ways of producing our products. If we look at a work breakdown by facility and manloading—considering a spectrum from digital modeling and simulation to open air range testing—we find that open air testing accounts for only about 30 percent of the work we do—but it accounts for over 60 percent of our manpower. Since manpower is a high-leverage commodity, this highlights a real potential for reducing the cost of doing business. We can pursue two strategies: We need to either dramatically reduce the manpower costs associated with open-air testing, or we need to reduce the amount of open-air testing. We have chosen to emphasize the latter option because we not only reduce the cost, we also get better results.

Our basic concept of testing uses a building block approach that starts with digital modeling and simulation to predict the test item's responses before any hardware exists. As hardware is produced, the hybrid testing phase begins where the test item is subjected to increasingly more complex, simulated environments. Our approach to better testing is to depend on hybrid environments because we get a better understanding of the system under test at a lower cost. Hybrid testing begins with basic parametric measurements of the components and subcomponents, continues through the integration of those components into subsystems and proceeds to the installation of the systems in their host platforms in a synthetic test environment. The final proof remains in the open-air testing, but we believe this very expensive stage should not begin until their is high confidence we know how the system works. Of course, simulation and analysis provide the reference base throughout the testing process and are the repository for our understanding of the system. This integrated approach to test and evaluation is the principle embodied in some of our premier test facilities: the Electronic Combat Integrated Test facility at Edwards AFB and the Air Combat Environmental Test and Evaluation Facility at Patuxet River.

Another side of decreasing the cost of testing is to increase the productivity of our assets. Three years ago the Air Force Developmental Test Center set the goal of achieving the same utilization rate for their test aircraft as the operational forces have.

This approach is not usually taken with a test fleet for a variety of reasons, but they were able to achieve this increased level of output in about a year. The real payoff came when they resized the test fleet to match the higher utilization. Because they now need fewer aircraft to fly the same number of sorties, they have been able to cut the fleet size in half while still flying the same number of test hours. With these actions, they were able to realize some very significant savings in maintenance manpower, with a direct reduction in infrastructure support costs.

Arnold Engineering Development Center, facing an aging test infrastructure and a growing maintenance backlog, is seeking to implement a non-bureaucratic maintenance management system addressing the availability, reliability, and affordability of their infrastructure. One of their principal focuses has been to acquire a modern Computer Maintenance Management System. The efficiency improvements this system promises has the potential for saving the center $49.5 million over 5 years. It is important however, that the process which the new system supports be appropriately reengineered before its introduction to avoid having a good tool supporting a bad process.

It is this sort of investment that turns us to the third pillar, **revitalization.** Most of our test facilities were built in the early stages of the Cold War. More than two thirds of the infrastructure is over thirty years old—with the average age being well over forty years. During the last twenty years, DoD's investment rate for the T&E facilities had been less than one third of the rate of investment in private industry and an order of magnitude below the investment rate for high technology industries. These facilities need to be revitalized to:

- Address testing of new technologies such as smart weapons, low observable systems, complex electronic systems, and space systems.

- Replace outdated technology and single Service approaches with state-of-the-art instrumentation and facilities that satisfy joint Service needs.

- Replace inefficient, labor intensive T&E resources with modern, cost effective capability to meet the needs of the twenty-first century.

Today's weapons employ technology that was virtually unknown at the time most of our test capability was established and much of it is unsuited to the needs of modern flight testing. Just consider one underlying change affecting traditional aerospace—namely transformation from being principally focused on "aluminum bending" to becoming increasingly involved in large scale electronics system integration. The term aeronautics was originally coined to describe "air-flight" developments that grew in some ways out of "nautical" principles. When airframes began yielding in part to space vehicles, the term "aerospace" was born. Today we are no longer dealing with aerospace; we are in what might more accurately be characterized as the "aeroelectrospace" era.

As part of this revolution, the fraction of electronics in defense equipment has grown from about one percent in World War I to about five percent in World War II to 45 percent today…and the fraction continues to increase. Correspondingly, about 10 percent of the weight and one-third of the cost of modern combat aircraft are composed of electronics and related components. Principal among the latter is software—a substance that weighs nothing but costs inordinately. I would contend that the "aeroelectrospace" era is fundamentally different from the one in which the Flight Test Center at Edwards AFB was conceived.

At the same time that our investments in T&E are declining, maintenance costs are increasing and productivity is decreasing due to age and outdated technology. For example, the Propulsion Wind Tunnel facility at Arnold Engineering Development Center faces declining availability and maintainability in several areas. For example, two old and inefficient electric induction motors driving the 16-foot transonic and supersonic tunnels' compressors are an Achilles heel of the facility's operations. These motors were designed over 45 years ago, are not environmentally friendly, and halt tunnel operations whenever they fail. A $65M sustainment program over the next 7 years will be required to correct this and other deficiencies but will reduce operating costs due to greater efficiencies, fewer subsystem failures, and reduced run time.

The impact of inadequate investment in test capabilities is reflected directly in our ability to affordably modernize the forces. The effect on acquisition programs is seen in several ways:

- Time to test is increased by the decrease in availability of older, more difficult to maintain test capabilities resulting in cycle time impacts on programs.
- Costs to test are increased because the lack of investment in the capabilities needed for emerging cost effective T&E methodologies.
- Risk in programs is increased as our test and measurement capabilities lag the technologies we are testing.

On the other hand, with proper investment in test facilities, we are achieving some significant successes through recently fielded systems that have increased both the effectiveness of our testing and its efficiency. Examples of this are the common airborne instrumentation system (CAIS) now flying on the F-18E/F, the Smart Munitions Test Suite—a mobile system critical to missile defense testing, and the Next Generation Target Control System (NGTCS) which will allow targets to be controlled by an interoperable system and permit their use at any range—whether testing or training. This is a key capability for many programs with the Aegis program office a prime beneficiary.

The benefits to be gained from innovative, modern T&E capabilities are manifold. The Naval Air Weapons Center at Patuxet River used the Air Combat Environmental T&E Facility to reduce flight test hours and cost by a third in testing equipment on board

the EA-6B aircraft. The Aerial Cable Test facility at White Sands Missile Range has saved projects over $20M in the first year of operation by reducing missile firings and in-flight testing. At Eglin AFB, use of ground simulation led to a 35% reduction in cost and a 300% increase in data capture during flight test of the APG-63 radar.

Having embarked on this three-pronged approach to the consolidation and future planning for our test facilities, there are obviously many challenges facing the U.S. flight test community along the way—not the least of which are legal obstacles. New legislative authorities will likely be required in order to maximize the potential now held captive by a lengthy list of statutory requirements and regulations.

Undoubtedly one of the principal impediments to effective rationalization relates to the time required for this process to pursue the necessary coordination and determination—a time scale that simply is not compatible with the pressures of the environment in which we exist.

Long periods of uncertainty, where employees do not know for whom they will work, where they will work, and who will pay their pensions, are not conducive to high morale and enthusiastic performance. Similarly customers—program managers-- are reluctant to plan major test programs at facilities where it is uncertain what the future of that facility is going to be. And comptrollers are reluctant, in fact, down right resistant, to permit much needed investment in any facility that has a whisper of reduction in its air. We cannot continue to cut the tail off of the cat an inch at a time. If we do not decide on and proceed with a clear path for the future of our flight test resources, the decisions will be made for us—perhaps by default.

We must get on with it! Vision 21 with its three mutually supporting pillars: reduction, restructure, and revitalization, is the U.S.'s approach to the consolidation and future of our flight test facilities. I believe that

- A decisive plan is essential for the future of flight testing, and
- All three pillars are required for an effective plan.

Change has been likened to a dragon. You can try to fight it, but you most likely will end up losing and not surviving the battle. Or you can jump on its back and ride it. It may be a wild ride, but at least you'll be where its going when it gets there.

C-17A Avionics Flight Test Program

William J. MacLean, Captain, USAF
418 FLTS/DOEAC
60 North Wolfe Avenue
Edwards AFB, CA 93524
United States

A. Lawrence Dublenko, P. Eng.
Aerospace Engineering Test Establishment
4 Wing Cold Lake
Medley, Alberta T0A 2M0
Canada

I. Summary

To date, the C-17A is one of the most advanced military airlift aircraft in the world. The corresponding avionics have reduced the number of crewmembers in the cockpit from four to two, and at the same time have increased the pilot's awareness of his aircraft's capabilities. The DT&E avionics program introduced many challenges to efficiently and adequately test the system to a high level of confidence before releasing the capability to the user. The use of effective test team structure helped to make the test program as efficient as possible, and the many lessons learned were incorporated into the program as testing progressed. As complex as the C-17A avionics suite is, it is a highly capable system with room for growth to increase future capability.

In December 1979, the United States Department of Defense launched the Cargo-Experimental (CX) program to define the capabilities needed in a new strategic airlift aircraft. The result was the C-17A Globemaster III which incorporates supercritical airfoil technology and winglets for long-range cruise performance as well as large externally blown flaps, full-span leading edge slats, spoilers, high sink-rate landing gear, anti-skid braking, and thrust reversers for rapid tactical descent and enhanced performance at short airfields. Further, the advanced C-17A integrated avionics suite, which consists of more than 60 remote terminals on nine different MIL-STD-1553 busses, enables an aircrew of only two pilots and one loadmaster to carry out the C-17A long range heavy airlift mission.

Test mission planning, test conduct, and analysis used both traditional and new test techniques to successfully accomplish the test mission. Lessons learned have been mostly in the realm of test planning and preparation. The sheer number of test points for the entire program (8000 total) and the manner in which testing was divided into aircraft systems contributed to inefficiencies in test flights.

The C-17A avionics flight test program introduced many challenges to efficiently and adequately test a complex integrated avionics system to a high level of confidence before releasing capability to the user. The use of an effective test team structure and test planning helped to make the test program as efficient as possible, with many lessons learned being incorporated into the program as testing progressed. As complex as the C-17A avionics suite is, it is a highly capable system with room for growth to increase future capability.

II. Introduction

In December 1979, the United States Department of Defense launched the Cargo-Experimental (CX) program to define the capabilities needed for a new strategic airlift aircraft. Based on the years of experience with the C-130, C-141, and the C-5, the United States Air Force, Army and Marine Corps prepared a list of requirements for a new airlifter which should meet these requirements. The capabilities included the ability to deliver heavy payloads over long distances into small, austere airfields. What came about was the C-17A Globemaster III which is capable of airdropping outsize cargo.

Designed to be operated by two pilots and one loadmaster, the C-17A incorporates supercritical airfoil technology and winglets for long-range cruise performance, as well as large externally blown flaps, full-span leading-edge slats, spoilers, high sink-rate landing gear, antiskid braking, and thrust reversers for rapid tactical descent and enhanced performance at short airfields.

To allow a cockpit crew of only two pilots to handle such an advanced and complex aircraft (Figure 1), a sophisticated and integrated avionics system had to be developed and then tested. This final task--flight testing of the C-17A avionics systems--is the focus of this paper.

III. Avionics System Description

The C-17A avionics are comprised of 4 major systems consisting of 60 remote terminals on 9 different MIL-STD-1553 data buses, with the addition of ARINC 429 buses for direct communications on the flight control and mission computer keyboard systems. The four major systems--the mission computer, warning and caution, integrated radio management, and flight control subsystem--each have a primary computer that acts as controller for the MIL-STD-1553 data buses as shown in Figure 2. These complex systems allow for a reduced aircrew by performing functions traditionally carried out by navigators and flight engineers.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

Mission system functions are comprised of system management and monitoring, aircraft guidance, database management, crew interface and display processing, flight planning, communications management, navigation and aircraft performance prediction. The mission system, also referred to as the Mission Computer/Electronic Display System (MC/EDS), receives aircrew input and displays information using the following equipment:

1. Two multifunction control panels (MFC);
2. Four multifunction displays (MFD);
3. Two head-up displays (HUD);
4. Three mission computers(MC);
5. Four mission computer displays (MCD); and
6. Two mission computer keyboards (MCK).

Functionally, the MC/EDS is divided into two parts: the EDS and the mission computer subsystems. The EDS consists primarily of the MFDs, HUDs, and MFCs. The mission computer subsystem consists of three identical MCs that are connected to both of the mission buses and continuously cross-check each other for accuracy. Normally MC1 is the master controller for both mission buses while MC2 and MC3 are on standby for immediate backup. Any failure of one MC alerts either one of the other MCs to take over control of the mission buses. Thus, the system provides triple redundant control of the two mission buses and associated flight management/mission functions.

The MCs provide the input/output, computational control, data storage, and built-in-test (BIT) capability to perform navigation, guidance, takeoff and landing operations, weight and center of gravity computations, airdrop, rendezvous, station keeping, and flight operations. They also provide voice-message countdowns during airdrop and aerial refueling rendezvous.

The MCs are accessed manually by keyboard entry through the MCK and MCDs. The MCDs are functionally identical and divided into two pairs, each pair controlled by one of two MCKs as shown in Figure 3. Two MCDs and an MCK form a set, one set for each pilot. Provisions were made for the addition of a third MCK and a fifth MCD located in the aft of the center console at the additional crewmember's (ACM) position. The MCK features a full alphanumeric keyboard with special purpose keys. Data entries are displayed in a scratchpad field on an active MCD prior to sending the data to the MC.

Mission mode data encompasses the items required for successful completion of the planned mission including definition of the lateral and vertical flight plan, operation of the navigation sensors, and data needed to execute performance functions (e.g. takeoff and landing data) and to display the results of those computations.

A stationkeeping equipment system (SKE), managed by the Mission Computer, provides formation flight capability with up to 17 other SKE-equipped C-17, C-141, or C-130 aircraft. The SKE, in conjunction with the Mission Computer, performs five functions: (1) the display of relative range and azimuth in the formation on the MFD; (2) an integral signaling capability for the transfer of flight commands and other data to facilitate coordinated changes of the formation's flightpath; (3) audio and visual proximity warning system to signal the presence of SKE-equipped aircraft intruding within a selectable zone; (4) the provision of flight director and autopilot/autothrottle coupling signals; and (5) guidance to a drop zone using a AN/TPN-27 ground based zone marker.

The warning and caution system (WACS) consists of two redundant warning and caution computers (WCCs), a separate MIL-STD-1553 data bus, a warning annunciator panel (WAP), a central aural warning system (CAWS), two glareshield-mounted master WACS displays, and a WACS failure light.

Warning and caution computer No. 1 is powered by the battery bus, allowing the system to be fully operational during emergency power situations. WCC No. 2 is powered by the No.3 DC avionics bus. When power is applied to the aircraft, the WCCs perform a self-test and the first one to initialize takes over as the WACS bus controller with the other computer acting as an on-line backup. The WAP, located on the pilots' overhead control panel, receives information from the WCCs and displays color-coded annunciations of aircraft system conditions as shown in Figure 4. Warnings are displayed in red, indicating a condition that requires immediate corrective action while cautions are displayed in yellow, indicating that crew attention is required but immediate action is not necessary. Advisories are displayed in green, indicating a safe or normal condition. Aural annunciations are provided by the CAWS and include such messages as count-downs for airdrop and rendezvous, as well as warnings from the ground proximity warning system.

The integrated radio management system (IRMS), shown in Figure 5, consists of:

1. Two UHF radios that operate independently, one with HAVEQUICK capability and the other with higher power output for SATCOM
2. Two VHF AM/FM radios that operate independently
3. Two HF radios
4. Three secure communications processors, two for UHF/VHF and one for HF communications
5. One UHF/SATCOM connection in the cargo bay for airborne ground force tactical communications
6. One passenger address (PA) system
7. One identification-friend-or-foe (IFF) transponder
8. One emergency locator transponder (ELT)
9. Two navigation receivers each consisting of VHF omnirange (VOR), instrument landing system (ILS), and marker beacon (MB) receivers
10. Two distance measuring equipment (DME) interrogators
11. One tactical air navigation (TACAN) receiver
12. One automatic direction finding (ADF) receiver

The heart of the IRMS are the two communication control units (CCU) that act as controllers for the two communication MIL-STD-1553 data buses.

The C-17A has a digital electronic flight control system (EFCS) with a mechanical system for backup. The EFCS has four separate flight control computers (FCCs) that receive pilot inputs, combine them with other sensor data, and then apply servo position commands to the control surface actuators. The automatic flight control system (AFCS) is a subset of the EFCS and provides crew relief and guidance functions that are implemented as a flight director, an autopilot, and an autothrottle. The AFCS can also be coupled to the mission computer to allow flight plans, VOR courses, station keeping, and instrument landing approaches to be flown hands-off. The AFCS control panel (AFCP), shown in Figure 6, is the primary control for AFCS mode selections.

When engaged, the autopilot provides pilot-selectable outer loop control modes for both longitudinal and lateral axes, as well as pitch and roll inner loop stability augmentation, yaw damping, and turn coordination functions. Pilot monitoring of autopilot performance is available through control stick motion cues provided by the autopilot control stick pitch and roll electromechanical actuators, which move the control sticks in response to control inputs. The autothrottle system (ATS) provides pilot-selectable control modes for the thrust axis using an autothrottle electromechanical actuator, which repositions all four engine thrust levers. The pilot monitors the ATS through throttle position. Selected flight modes for pitch, roll, and thrust are displayed as flight mode annunciators (FMA) on the corners of the HUD and the primary flight display (PFD) of the MFD (Figure 7). These cues are used by pilots to manually control the aircraft's pitch, roll, and thrust.

The AFCS operates in two different control configurations, depending on the mode of flight. When flaps are set at 1/2 or less, the C-17A is in a frontside control mode with flightpath controlled by pitch and airspeed controlled by thrust. When in the powered lift configuration, the flaps are at 3/4 or greater, the flightpath is controlled by thrust and the airspeed is controlled by pitch. A large externally blown, double-slotted flap is used to generate powered lift by directing engine exhaust over the flaps to allow the aircraft to operate at lower airspeeds for airdrop and approaches.

IV. Avionics Flight Test Program

Test planning was carried out in 1985 by the System Program Office (SPO), McDonnell Douglas Aerospace (MDA) and Air Force Flight Test Center (AFFTC) personnel. The test plan was organized by dividing test points into groups according to aircraft systems and then creating system test documents called detailed test information sheets (DTIS). The avionics test program was divided along avionic system lines into 30 DTISs as shown in Table I.

Mission and Flight Control Systems	**Integrated Radio Management System**
	HF Radios
Autopilot and Autothrottles	UHF SATCOM
HUD and MFD	VHF AM/FM Radios
Mission Computer/IRS/GPS	UHF AM and HAVEQUICK Radios
Weather RADAR	Public Address System
RADAR Altimeter	Intercommunication System
I-Band Transponder	Secure Voice
Station Keeping Equipment	Static Discharge
	Cockpit Voice Recorder
Warning and Caution	Integrated Radio Management System
	Emergency Locator Transmitter
Aural Alerting System	Instruments/Controls/Displays
Visual Alerting System	Marker Beacon
Ground Proximity Warning System	Instrument Landing System
Standard Flight Data Recorder	VHF Omni Range
	Distance Measuring Equipment
	Identification Friend or Foe
	ADF / UHF
	Electromagnetic Compatibility

Table I - Avionics Detailed Information Sheets

Block No.	Capability Release
Block 1/2	VFR local
Block 3	IFR Local
Block 4	VFR/IFR CONUS
Block 5	VFR/IFR Overseas
Block 6	Forward Operating Base
Block 7	Air Refueling
Block 8	Day Single Ship Low Level 1000 AGL
Block 9	Night Single Ship Low Level 1000 AGL
Block 10	Station Keeping
Block 11	Steep Approach and Landing
Block 12	Airdrop
Block 13	Single Ship Low Level 300 AGL
Block 14	Tactical Descent
Block 15	Mission Computer Directed Approach

Table II - Block Capability Releases

The C-17A flight test program was then carried out at Edwards Air Force Base, California, using a Combined Test Force (CTF) consisting of MDA, AFFTC and Air Force Operational Test and Evaluation Center (AFOTEC) personnel. The first aircraft was delivered to Edwards AFB with a limited flight envelope for visual meteorological conditions only. The first test flight occurred in September 1991.

As the test program progressed and the first production aircraft was delivered to an operational squadron at Charleston AFB in June 1993, it became imperative to carry out testing in a manner that allowed release of incremental operational capability. To this end, portions of the individual DTISs were combined into test blocks to allow incremental delivery of mission capabilities. Each required capability was analyzed to determine which systems and associated tests were needed to release the capability. The test points were also selected from the DTISs in such an order to ensure both a proper buildup procedure and a logical order of test was followed for each of the avionic systems. The resulting capability block releases are shown in Table II.

Six C-17A aircraft were used for the DT&E program, each as a dedicated test bed with specialized instrumentation for specific system or performance evaluations. One production aircraft was modified to accept instrumentation to specifically provide an avionics testing capability. A data acquisition system monitored and recorded data from the production model C-17A's seven MIL-STD-1553 and eight ARINC 429 data buses. Data acquisition instrumentation equipment consisted of one Programmable ConditioningUnit (PCU) comprised of a pulse code modulation (PCM) encoder, a 16 card slot chassis, six 1553 bus interface cards, two ARINC 429 interface cards (four channels per card), and one Time Code card for imbedded time and event marking. Part way through the program, the PCU was upgraded to an analog and discrete capability. This consisted of 16-channel differential analog inputs, an 8-channel bridge conditioning unit, and 48 discrete inputs. The required parameters were sampled, combined into a serial pulse code modulated data stream and recorded on a 14-track, 15-inch, reel to reel AR 1700 data recorder, which included a remote control panel with tape remaining indicator. To monitor and capture GPS data information, a Global Positioning System Receiver Buffer Interface Unit (GRBI) was utilized.

A video camera system was implemented to monitor and record HUD, cockpit, and MFD data. This system consisted of one HUD camera, two MFD cameras, and one cockpit-view camera (all ELMO MN401E cameras), two video time inserters, four VCRs and four camera control units. These miniature video cameras monitored HUD and MFD data, which was then recorded on HI8 video cassettes along with aircraft intercom audio on the edge track of the video tapes. A time-of-day display and event marker switch provided event correlation capabilities.

Test flight planning, conduct, and analysis used both traditional and new techniques to successfully accomplish the test mission. Aircraft capability block releases were mapped onto program milestones. In preparation for each capability release, regression test points plus those DTIS points identified for the block release were translated into test cards. Cognizant system engineers and flight test engineers (FTEs) prepared the test cards and then stacked them into mission profiles with priority placed on maximizing the test efficiency based on fuel, altitude, time, and phase of flight. Test card generation and flight planning were enhanced by the use of a new program called TEST_PLAN®, which operated on SUN workstations (Figure 8). New software loads were tested in the MDA flight hardware simulator (FHS) as a first step in software validation prior to flight test. During this stage of testing, cognizant engineers monitored the FHS tests and incorporated some of the results into flight test, thereby correcting many problems long before the software build ever reached the aircraft.

Safety planning was also paramount, with each new type of test requiring the identification of risks, a completed Test Hazard Analysis, and risk minimization procedures. Weekly

test card reviews allowed aircraft managers, flight test engineers, systems engineers and pilots to review upcoming test card decks. A Flight Readiness Review the day prior to a test flight and the pre-flight brief the day of the flight made for two more opportunities for all involved parties to review card decks and the status of the aircraft.

During test flights, onboard system engineers and pilots enabled qualitative assessments for some test points (e.g., the adequacy of a navigation display); however, most test points required post-flight data analysis to determine mission effectiveness and specification compliance. Post flight debriefs allowed for a review of aircraft status and preliminary comment on the conduct and results of each test point by pilots, FTEs, system engineers, maintenance personnel and the aircraft manager. Data tapes were processed immediately after flight by ground personnel, with flight data extracted from aircraft data tapes and transferred to computer data files. System engineers could then submit data requests for parameters and time slices for each test point to obtain time history plots as shown in Figure 9. These were then used to assess system performance for mission capability and specification compliance per the Air Vehicle Specification.

V. Test Results and Lessons Learned

During the DT&E program, the initial immaturity of the avionics systems initiated many changes and improvements to system software. Flight director and autothrottle takeoffs using the MFD or HUD were acceptable in all configurations, giving smooth guidance to acquire scheduled climb-out speeds. Vertical speed select and hold, IAS/Mach select and hold, altitude select and hold, heading select and hold, turbulence, and split axis modes were also found to be satisfactory for frontside flight director and autocoupled operations. Early avionics testing revealed vertical speed oscillations in powered lift modes during airdrop operations, as well as poor guidance and pitch-up problems during mission computer directed airdrops. Further testing, which included the changing of certain gains, coupled with other software modifications, alleviated these problems, resulting in a stable platform for conducting airdrop operations. Other improvements made to system performance included reducing altitude loss during go-around and improved ILS approach performance.

I-band beacon and weather radar display control software originally contained compensation for object movement between radar sweeps, which scrolled all radar returns smoothly down the radar display at a rate proportional to the C-17A groundspeed. However, if radar or I-band beacon returns were received from an object whose speed relative to the C-17A was small, the software still applied the groundspeed correction before displaying the object. This compensation resulted in the object scrolling down the display at the C-17A groundspeed and then being returned to its correct position with each radar sweep. At long ranges, the effect on the display was not noticeable but as the range closed to within 10 nautical miles, these returns, usually aerial refueling aircraft I-band beacons, suffered from display jitter. Follow-on display software has since corrected this problem, resulting in smooth and accurate display updates.

During formation flight, the station keeping equipment software is capable of repositioning wing aircraft from one side of the lead aircraft to the other side using the autopilot coupled to the mission computer, or by providing flight director guidance for the pilot to follow. The original SKE position change guidance did not take into account lead aircraft wing tip vortices and thus could not be used in its original form. Until later software upgrades, pilots were required to disengage the mission computer and autopilot or ignore the flight director guidance and manually fly over the lead aircraft vortices when changing positions.

Another issue that arose was that of the correct interpretation of the Figure-of-Merit (FOM) for airdrops or approaches. The FOM is an integer between one and nine, inclusive, that represents the navigation accuracy currently achieved through the use of GPS and/or IRUs. Initially, there was uncertainty in how to interpret this number and as to whether GPS was in the navigation solution or not. Further uncertainty was caused by having different FOMs representing accuracies for IRU, GPS, and MC navigation solutions. Procedural changes remedied the problem initially and current mission computer software has simplified and standardized the various FOM accuracies previously mentioned. Recent HUD software upgrades have included the display of the FOM on the HUDs during airdrop and approach modes. A future software block upgrade will revamp the FOM and base it upon aircrew input into the design process.

Many of the changes and improvements to system software revolved around user interface and human factors issues. Included in the human factors assessments of the avionics systems was that the mission computer interface required improvement to enhance utility. Examples of such interface problems included the mission computer not accepting all parachute types used by the U.S. Army, the mission computer not displaying takeoff and landing data (TOLD) values when they were out of limits (thus not informing pilots of critical field lengths or weight constraints), awkward data entry and page selection for flight planning using the mission computer, and the mission computer having poor data tolerance when in a tactical descent so that a waypoint in the flight plan would not be sequenced if the bottom-of-descent was not reached exactly. In spite of these identified user interface difficulties, experienced aircrew viewed the mission computer as better than systems on other existing aircraft, and to be a valuable tool for flight planning, navigation, airdrop, directed approaches and rendezvous during air refueling.

The AFCP was also found to be marginal from a human factors standpoint. Knobs for the control of airspeed, heading and altitude selections were physically the same and located close together, making it difficult to discriminate amongst the knobs by touch only. Many of these problems, as well as other

similar inconveniences discovered in flight test, have been corrected in subsequent software and hardware updates.

Lessons learned have been, for the most part, in the realm of test planning and preparation. During airdrop testing, with tests split up by system, end-to-end airdrop accuracy was overlooked. Avionics DTISs tested the aircraft's ability to fly to the computed air release point (CARP) while the mission systems DTIS looked at the accuracy of the point of impact. Test point inefficiency was also a problem. With similar test points flown under several different DTISs, the sheer number of test points (more than 8000 in total) made it difficult to fly a common test point to provide data for several different DTISs. Tools such as TEST_PLAN® and the FHS were available to ease the test planning workload, but initially the test team's workload did not allow them to fully utilize these tools. In follow-on testing, test card decks are being generated using TEST_PLAN® and then are "flown" in the FHS prior to the actual test flight. This has greatly improved the test card procedures and has revealed some problems on the ground rather than in flight. Flying the flight test profiles in the simulator first has also generated monetary savings. Better crew preparedness and the early discovery of problems in the simulator have resulted in the more efficient use of actual flight time.

VI. Follow-On Avionics Flight Test

Several upgrades are planned for C-17A avionics to increase the aircraft's capability. These upgrades will increase the long-term affordability and reliability of the aircraft, as well as address the issue of the universality between aircraft in the United States Air Force inventory:

a) SATCOM - satellite communication improvements;
b) SURE-COMM - improved wireless intercom system;
c) SKE 2000 - improved station keeping equipment;
d) CIP - core integrated processor upgrade;
e) All Weather Precision Approach Demonstration - Category IIIa Differential GPS capability;
f) GPS/RAIM - global positioning system receiver autonomous integrity monitoring.

The U.S. Air Force is upgrading its satellite communication capability with SATCOM radios that operate using 5kHz channel spacing. Other improvements include a demand assigned, multi-access (DAMA) capability. The C-17A will be upgraded to accommodate these new SATCOM capabilities.

Upgrades to the current C-17A wireless intercom system will by made with the use of an improved unit, called SURE-COMM, which is a light weight, hands-free, full duplex wireless communication system. The SURE-COMM unit incorporates a receiver/transmitter box which is carried on the loadmaster's belt, a design change which reduces the weight of the headset. The upgrade will also reduce procurement and lifecycle costs for the C-17A fleet.

The current C-17A SKE equipment uses thirty-five-year-old year old technology. The SKE 2000 upgrade uses new technology, which will reduce overall system weight by sixty-four pounds and improve system performance over water where multi-path radio propagation can affect current system performance.

Implementation of the core integrated processor upgrade will reduce the number of C-17A mission computers from three to two. The two new MCs will utilize 1990s computer technology, reducing weight and increasing computing power by a factor of more than eight.

To further the C-17A's ability to utilize short, austere airfields, under almost any weather condition and in possibly remote areas of the world, an All-Weather Precision Approach Demonstration is planned for the Spring of 1997. The goal is to develop a Differential GPS (DGPS) based All-Weather Precision Approach capability on the C-17, using a local area DGPS, military Y-code based system. Eventually, a demonstration will be completed of a HUD based wide area Category IIIa DGPS with full integrity monitoring and be compatible with the Federal Aviation Administration Wide Area Augmentation System (WAAS).

Finally, the current GPS has no receiver autonomous integrity monitoring (RAIM) capability nor any fault detection and exclusion (FDE) capability to identify and exclude faulty satellites from the navigation solution. The new GPS will be RAIM/FDE capable and will reside on a circuit card in a new IRU box. These improvements will reduce weight and increase the reliability and maintainability of the GPS.

VII. Summary

To date, the C-17A is one of the most advanced military airlift aircraft in the world. The corresponding avionics have reduced the number of crewmembers in the cockpit from four to two, and at the same time have increased the pilot's awareness of his aircraft's capabilities. The DT&E avionics program introduced many challenges to efficiently and adequately test the system to a high level of confidence before releasing the capability to the user. The use of effective test team structure helped to make the test program as efficient as possible, and the many lessons learned were incorporated into the program as testing progressed. As complex as the C-17A avionics suite is, it is a highly capable system with room for growth to increase future capability.

VIII. Glosssary of Terms

ACM	Additional Crewmember
ADF	Automatic Direction Finding
AFCP	Automatic Flight Control Panel
AFCS	Automatic Flight Control System
AFFTC	Air Force Flight Test Center
AFOTEC	Air Force Operational Test and Evaluation Center
AM	Amplitude Modulation
ARINC	Aeronautical Radio Incorporated
ATS	Autothrottles
BIT	Built-In-Test
CARP	Computed Air Release Point
CAWS	Central Aural Warning System
CIP	Core Integrated Processor
CCU	Communication Control Unit
CTF	Combined Test Force
CX	Cargo Experimental
DAMA	Demand Assigned, Multi-Access
DGPS	Differential Global Positioning System
DTIS	Detailed Test Instruction Sheet
DT&E	Developmental Test & Evaluation
EDS	Electronic Display System
EFCS	Electronic Flight Control System
ELT	Emergency Locator Transponder
FAA	Federal Aviation Administration
FCC	Flight Control Computer
FDE	Fault Detection and Exclusion
FHS	Flight Hardware Simulator
FM	Frequency Modulation
FMA	Flight Mode Annunciator
FOM	Figure-of-Merit
FTE	Flight Test Engineer
GPS	Global Positioning System
HF	High Frequency
HUD	Head-Up Display
IAS	Indicated Airspeed
IFF	Identification-Friend-or-Foe
ILS	Instrument Landing System
IRMS	Integrated Radio Management System
IRS	Inertial Reference System
IRU	Inertial Reference Unit
LAPES	Low Altitude Parachute Extraction System
MB	Marker Beacon
MC	Mission Computer
MCD	Mission Computer Display
MCK	Mission Computer Keyboard
MDA	McDonnell-Douglas Aerospace
MFC	Multifunction Control Panel
MFD	Multifunction Display
MIL-STD	Military Standard
PA	Passenger Address
PCM	Pulse Code Modulation
PCU	Programmable Conditioning Unit
PFD	Primary Flight Display
RAIM	Receiver Autonomous Integrity Monitoring
SATCOM	Satellite Communications
SKE	Stationkeeping Equipment
SPO	System Program Office
TACAN	Tactical Air Navigation
TOLD	Takeoff and Landing Data
UHF	Ultrahigh Frequency
VCR	Video Cassette Recorder
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System
WACS	Warning and Caution System
WAP	Warning annunciator Panel
WCC	Warning and Caution Computers

VIII. List of References

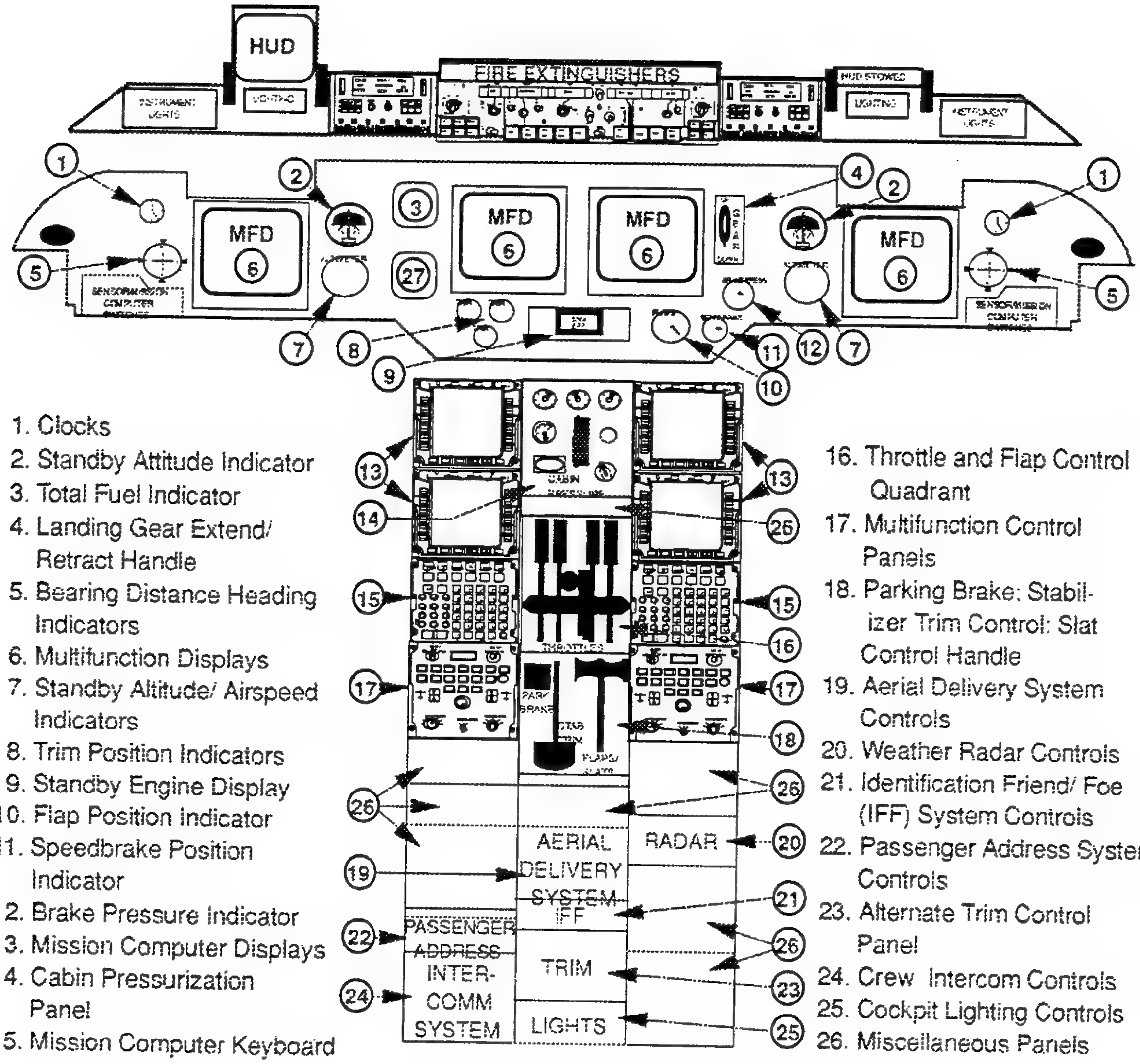
1. Boyd, Alfred H. and Brown, Steve, C-17A Communications System Evaluation, AFFTC-TR-94-28, Edwards AFB, California, October 1995.

2. Fabbro, Alexandria, C-17A Automatic Flight Control System Evaluation, AFFTC-TR-95-09, Edwards AFB, California, August 1995.

3. MacLean, William J., First Lieutenant, USAF, C-17A Mission Computer Evaluation, AFFTC-TR-95-04, Edwards AFB, California, July 1995.

4. Pick, Jonathan, C-17A Warning and Caution System Evaluation, AFFTC-TR-95-21, Edwards AFB, California, October 1995.

5. C-17A Detailed Test Information Sheet for Mission Computer, Inertial Reference System (IRS), and Global Positioning System (GPS), TIS F3462-01, Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach, California, revised 8 September 1994.



1. Clocks
2. Standby Attitude Indicator
3. Total Fuel Indicator
4. Landing Gear Extend/ Retract Handle
5. Bearing Distance Heading Indicators
6. Multifunction Displays
7. Standby Altitude/ Airspeed Indicators
8. Trim Position Indicators
9. Standby Engine Display
10. Flap Position Indicator
11. Speedbrake Position Indicator
12. Brake Pressure Indicator
13. Mission Computer Displays
14. Cabin Pressurization Panel
15. Mission Computer Keyboard
16. Throttle and Flap Control Quadrant
17. Multifunction Control Panels
18. Parking Brake: Stabilizer Trim Control: Slat Control Handle
19. Aerial Delivery System Controls
20. Weather Radar Controls
21. Identification Friend/ Foe (IFF) System Controls
22. Passenger Address System Controls
23. Alternate Trim Control Panel
24. Crew Intercom Controls
25. Cockpit Lighting Controls
26. Miscellaneous Panels

Figure 1 C-17A Cockpit Layout

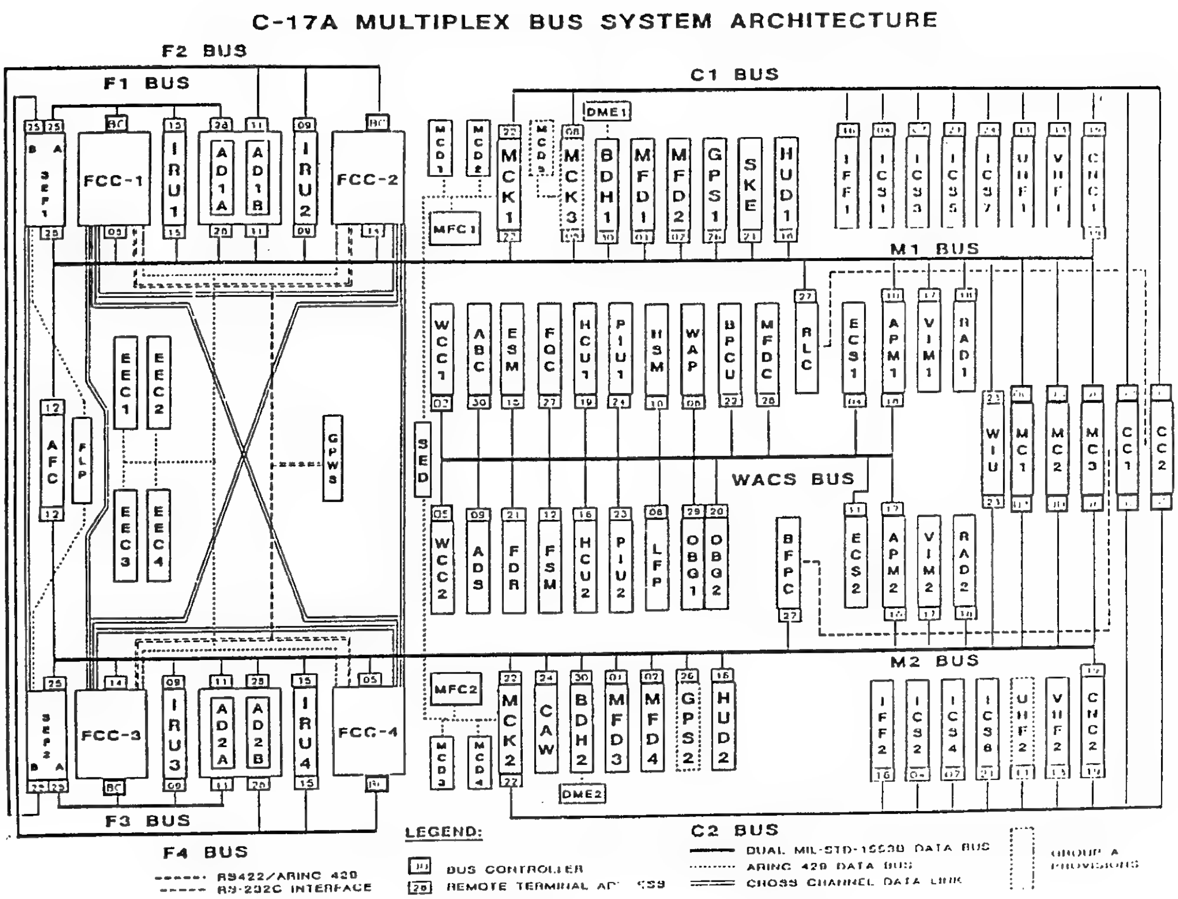


Figure 2 C-17A Avionics Bus Diagram

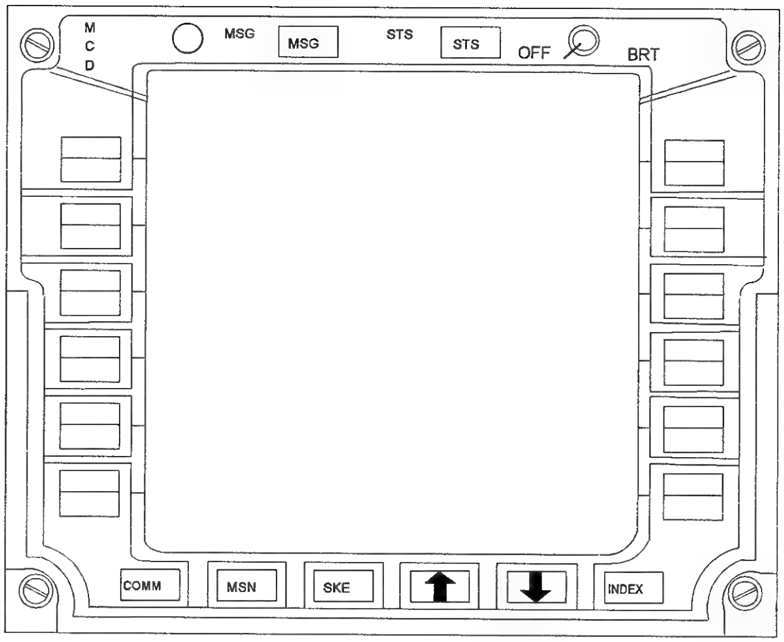


Figure 3a Mission Computer Display

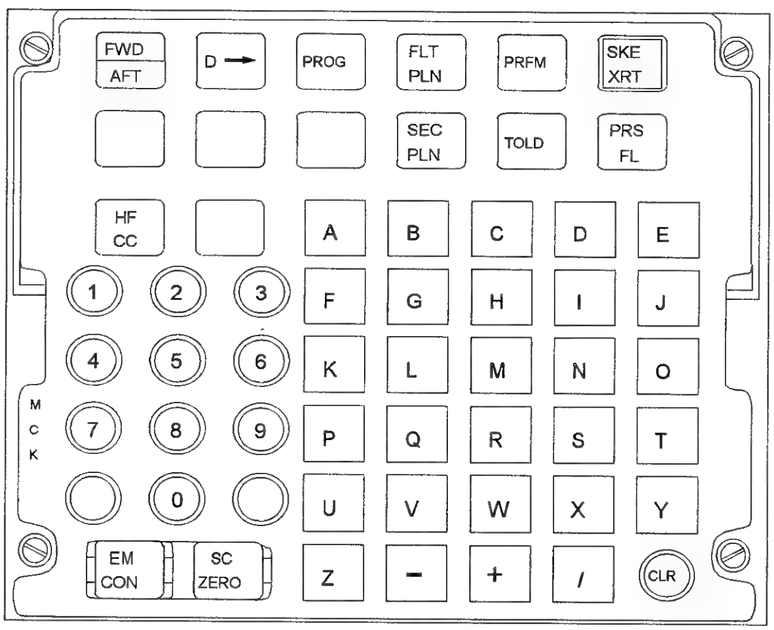


Figure 3b Mission Computer Keyboard

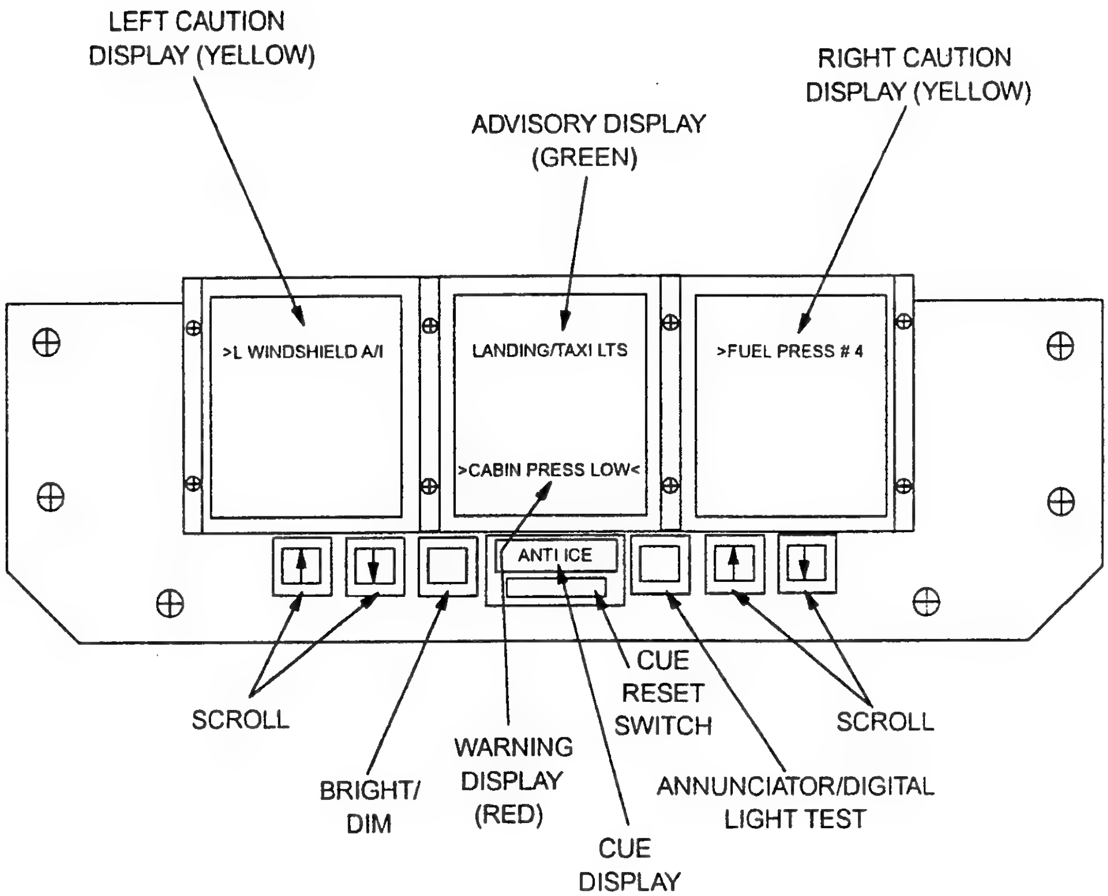


Figure 4 C-17A Warning Annunciator Panel

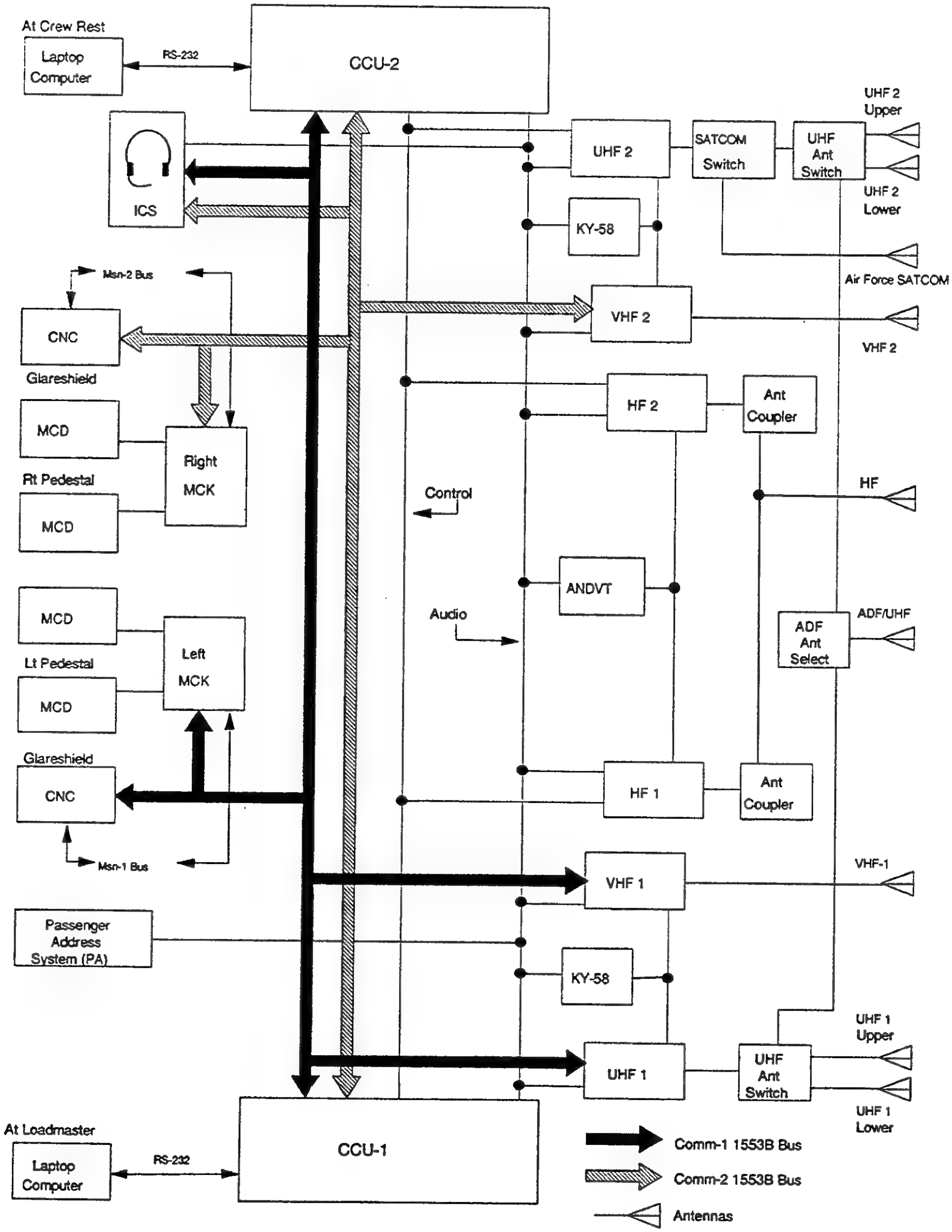


Figure 5 C-17A Integrated Radio Management System

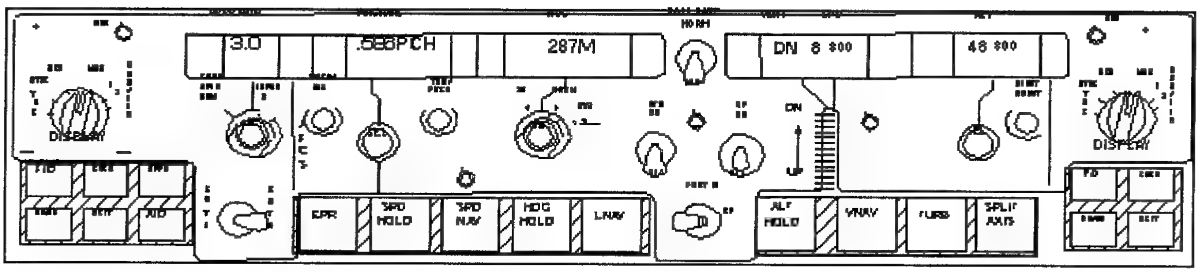


Figure 6 Automatic Flight Control System Control Panel

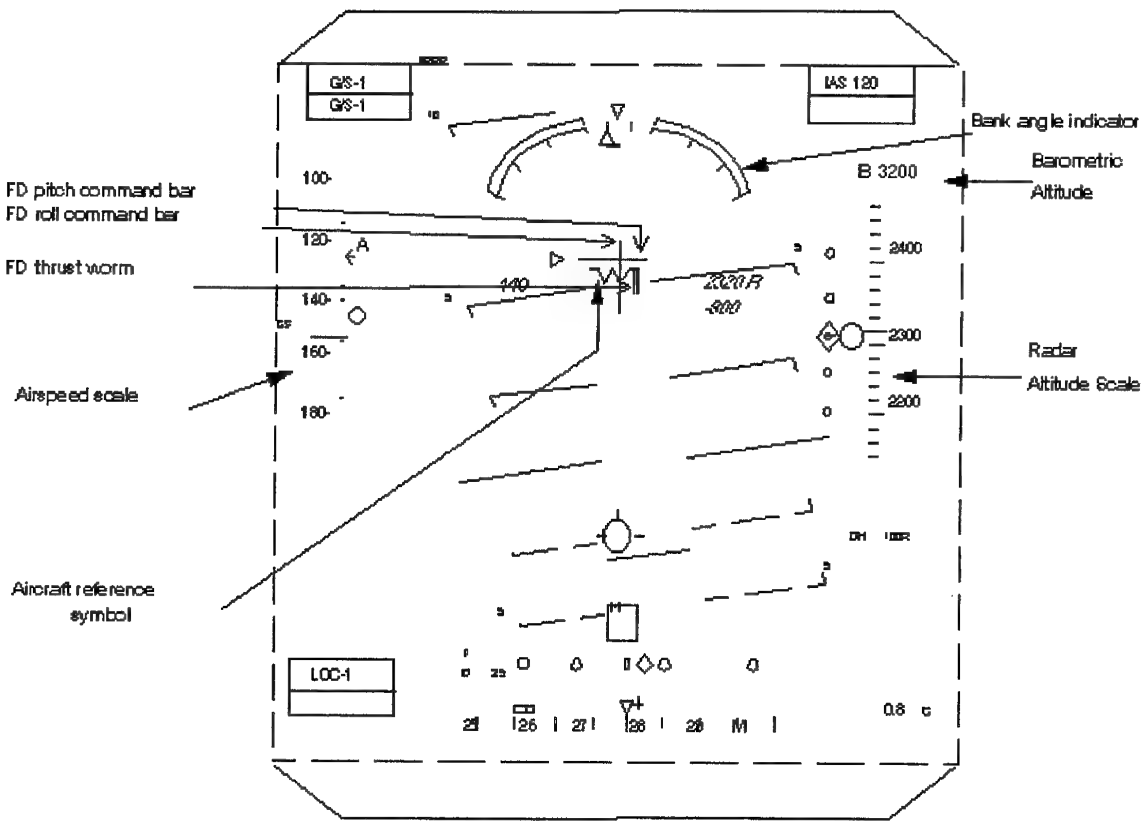


Figure 7 Head-Up Display Format

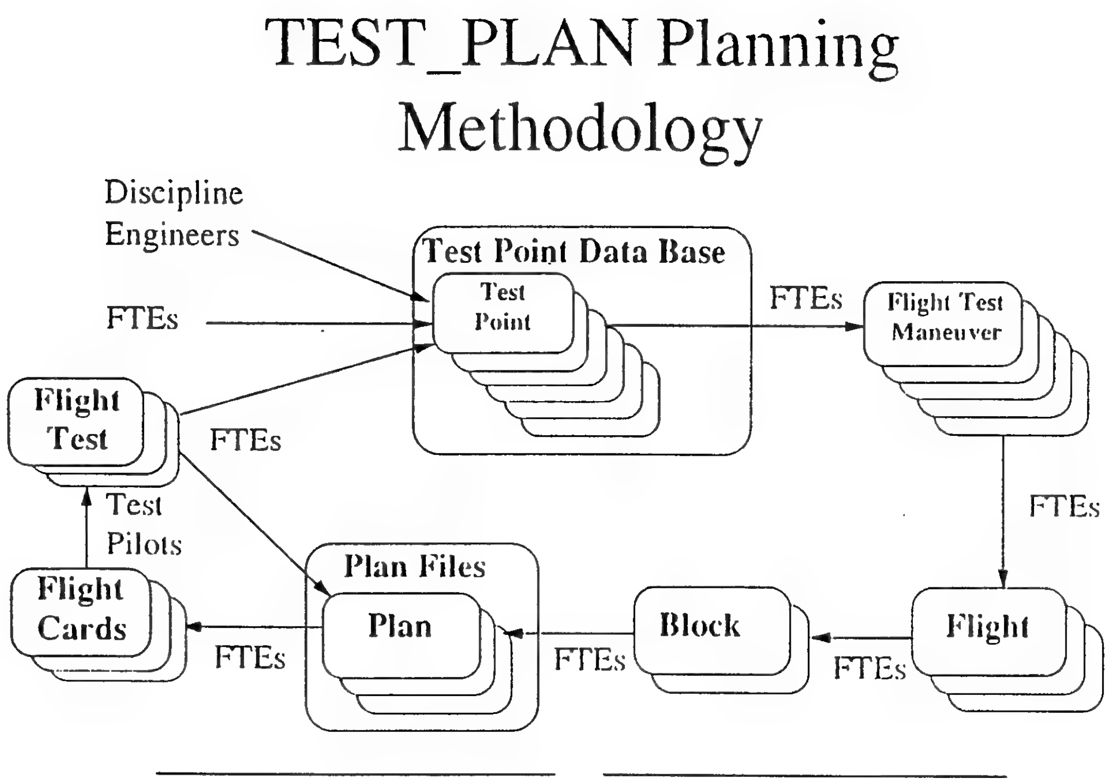


Figure 8 TEST_PLAN® Data Flow

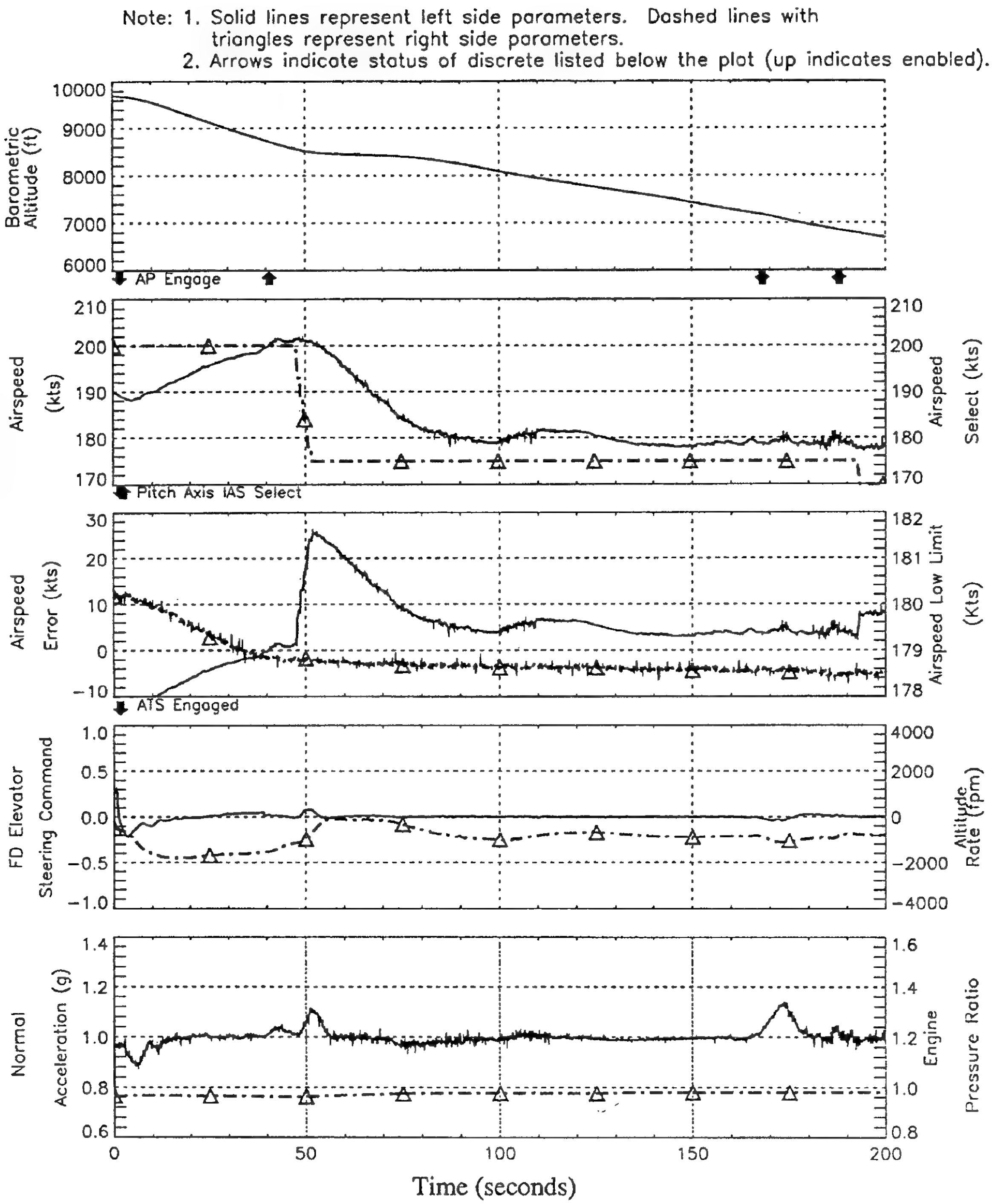


Figure 9 Time History Example

SYTRAM (SYstème de TRajectographie Multimobile) UNE NOUVELLE METHODE DE GUIDAGE DES AVIONS POUR LES ESSAIS MULTI-CIBLES

Cdt de MALLERAY
Base d'Essais d'Istres
13128 ISTRES AIR, FRANCE

1. RESUME

SYTRAM a été développé suite à un besoin du CEV de posséder un moyen de guidage autonome précis pour des essais multicibles. Les essais multicibles nécessitent souvent la réalisation de scénarios précis, difficiles voire impossibles sans un guidage fin et soutenu. Jusqu'à maintenant ces essais ont été fait avec l'aide de guideurs au sol transmettant leurs ordres par radio. Ils ne peuvent suivre précisément qu'un avion et jusqu'à 4 avions maximum. Au delà, plusieurs guideurs seraient nécessaires, mais la radio serait saturée. SYTRAM est une liaison montante et descendante. La liaison montante (60 KBIT/sec) du système SYTRAM permet la conception d'une fonction, baptisée "Guidage Autonome" qui devra produire des informations de guidage au profit des appareils en essais pour une mise en place autonome, i.e. sans recours à la phonie. 4 interfaces de guidage ont été développées, le HUD, le HDD, l'Instrumentation Classique et l'Audio. La loi de guidage, commune aux différentes interfaces, a été mise au point en simulateur en 3 semaines. Les essais en vol ont débutés avec 3 vols effectués sur ABE Mystère XX. Le but de ces essais a été de confirmer la faisabilité de la fonction de guidage autonome. L'interface HDD a été choisie pour les essais mais la capacité de modifier des coefficients de la loi de navigation en vol a été gardée. Enfin l'application de la symbologie HDD est en cours de réalisation sur un écran à cristaux liquides.

2. NOMENCLATURE

ABE	Avion Banc d'Essai
CEV	Centre d'Essais en Vol
HDD	Head Down Display
HEP	Hostile Equipier Piloté
HUD	Head Up Display
IC	instrumentation Classique
PPS	poste de Pilotage Simplifié

3. METHODE D'ESSAIS EN SIMULATION

3.1 - Environnement d'essai

Le Centre de simulation, du CEV offre des moyens de tester des matériels dans un environnement moins coûteux que le vol réel, avec de grandes capacités d'évolutions. La plate-forme HEP (Hostile Equipier Piloté) en est un exemple.

Pour des raisons de coût et de plan de charge des moyens de la <<Simulation>>, le PPS[1] M2000DA du HEP a été choisi comme support de l'évaluation. Il est divisé en deux parties : la cabine et la salle d'essai.

La cabine est constituée de :

⇒ Un cockpit type chasseur (M2000B) avec manche et manette M2000 S3

⇒ Un écran tactile de 21" sur lequel est présenté un tableau de bord synthétique

⇒ Un écran 1m x 1m placé devant la cabine pour la présentation de l'environnement frontal, et sur lequel peuvent être incrustées les information d'une VTH

La salle d'essai comprend :

⇒Trois consoles `Silicon' :
Recopie de l'environnement extérieur
Interface de contrôle de l'environnement tactique
Interface de guidage (logiciel de guidage trombone et configuration de la loi)

⇒ Une console INDY :
Programmation et recopie du tableau de bord

⇒ Une console Interphone avec la cabine :
Dialogue avec la cabine
Ecoute des messages audio

⇒ Une console Télévidéo avec les enregistreurs

[1]PPS : Poste de pilotage Simplifié ; reproduit avec des simplifications la cabine d'un M2000 pour servir de plastron piloté en face d'une cabine en évaluation.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

Limitations :

Malgré sa souplesse d'emploi et de programmation, cet outil a présenté des limitations qui ont certainement affecté les résultats de l'évaluation :

◊ Modèle avion : Les caractéristiques du modèle (M2000) ne sont pas aisément modifiable, de sorte que les avions tels que le Mirage III ou le Mystère XX n'ont pu être approchés.

◊ Le comportement du modèle existant, associé à la configuration matérielle de la cabine, présente des qualités de vol très gênantes sans PA. On assiste à de trop fréquents francs déréglages de trim de gauchissement ; ceux-ci associés à une nette difficulté de compensation en tangage ont augmenté de manière significative la charge du pilote (avis unanime). Ce problème, connu à la simulation, a été redécouvert en évaluation.

◊ Environnement `cibles' : le leader, mobile ` informatique' piloté via l'environnement tactique, effectue des départs en virage bien trop francs en regard à ce que ferait un pilote leader d'une patrouille, soucieux de ne pas détruire la géométrie de sa formation. La performance observée en a été affectée.

◊ Visuel : le PPS M2000DA, présente un visuel sur un secteur frontal seulement. Il n'a ainsi pas été possible de tester la surveillance du ciel dans des secteurs traditionnellement gourmands en temps.

◊ Enfin, l'absence de visuel latéral et de bruits de moteur (ou de conditionnement) ont privé le pilote d'informations << naturelles >> sur le comportement de son avion : la vision latérale donne des informations sur l'inclinaison et le roulis ainsi que sur l'altitude en TBA ; les bruits de cabine informent sur le régime moteur et ses variations.

Ces limitations amènent à garder une certaine réserve sur les résultats observés.

3.2 - Equipement en essai

Les matériels en essais sont en fait quatre configurations d'un programme permettant de :

Générer une interface synthétique sur l'environnement de la cabine au profit du pilote (planche de bord pour la VTB et l'instrumentation dite classique IC, visuel pour la VTH, Interphone pour l'audio).

Calculer les ordres et informations pour alimenter l'interface. Les gains et retards de la loi sont paramétrables. Les retards liés aux transmissions ont été intégrés.

Deux états ont été ont été retouchés après la première campagne pour prendre en compte les avis des pilotes : la VTB et l'Audio

VTB : la partie basse de l'image (SITAC) a été redéfinie pour que l'échelle en bas représente l'extérieur du cercle, pour que les mobiles ne sortent plus de ce cercle, et soient saturés à sa limite. Les changements d'échelle sont toujours gouvernés par la nominale, mais la distance de commutation est indiquée en pointillée.

Audio : la langue est anglaise (participation d'un pilote Anglais de l'EPNER pour l'enregistrement des messages élémentaires) ;la syntaxe a été épurée pour ne garder en automatique que les ordres de cap et vitesse et l'information <<en place>> (<<Nominal>>), et en manuel (sur demande pilote) la position relative du leader. A grande distance, le guidage en cap a été privilégié par rapport à la vitesse, dans un souci de clarté et donc de performance.

Les interfaces sont présentées en annexe au travers d'une image type (Annexe 1&2).

Par ailleurs, une cassette vidéo de présentation a été réalisée à partir de l'évaluation, permettant de mieux illustrer ces notions.

Remarque : Notons que la compatibilité du Guidage Autonome avec Trombone ou Vigie[2] a été aussi étudiée sur des profils spécifiques en transmettant directement sur les interfaces les ordres de navigation issus de ces logiciels d'aide au guidage.

---

[2] <<Trombone>>est un logiciel de GAO (guidage assisté par ordinateur) développé par le Centre de Simulation ; Vigie est un système de visualisation d'informations de trajectographie et d'assistance pour les guideurs ; il doit équiper les salles d'écoute Sytram à l'avenir.

Loi de navigation : Il s'agit d'une collision pure, bridée ensuite en vitesse en s'inspirant des principes des rassemblement de nuit : la vitesse de rapprochement est saturée en fonction de la distance (Cf. annexe 3)

Ici, l'audio se distingue des autres interfaces : la route et la vitesse (sol) de consigne sont converties en cap et vitesse indiquée de consigne dans les conditions instantanées du mobile. Un échantillonnage des informations gère la saturation auditive du pilote.

Pour les autres interfaces, la vitesse est convertie en accélération de consigne en la comparant à la vitesse observée du mobile.

3.3 Méthode

3.3.1 - Scénarios

Les profils de vol ont été standardisés pour comparer les résultats de chaque pilote; Ils tiennent compte de la réalisation usuelle et future des profils de vol multimobiles, à savoir :

⇒ rejointe du point de virage avec éloignement de synchronisation
⇒virage de présentation au cap de la passe
⇒ affinage de l'alignement avant la passe proprement dite
⇒ passe d'essai - maintien de l'alignement

Pour gagner du temps d'essai, il a été décidé de procéder comme suit :

⇒ initiation à une distance définie (pour rassemblement)
⇒ rassemblement (rejointe de la place)
⇒ si stable en place : évolutions du leader (<10° environ)
⇒ 2 grands virages ensuite (90° et 180°); (arrêt au retour en place)

Remarque sur les profils : il a été défini que si le dispositif évoluait franchement (n ≥ 2g, ou changements de cap trop amples), les tolérances sur les positions relatives devenaient nécessairement plus lâches voire inexistantes. Dans la mesure du possible, les << petites>> évolutions en cap sont restées inférieures à 10°, et à des inclinaisons ne dépassant pas 45°.

En parallèle, on joue sur l'environnement : hauteur de vol (MA ou TBA), demande d'actions pilote (mise en œuvre simulée de brouilleurs), surveillance du ciel (activation de plastrons visuels que le pilote doit annoncer). Le but est d'évaluer la disponibilité restante du pilote pour les tâches fondamentales du vol liées à la sécurité (vol VFR par exemple) lorsqu'il oeuvre pour tenir sa place.

Les gains ont été mis au point en début d'évaluation dans le but d'optimiser une configuration. Les retards simulés ont fait l'objet de phases spécifiques pour l'évaluation de leur impact sur la loi (0.3–, 1–,1.5– et 2– de retard ont été successivement injectées dans le système).

3.3.2 - Exploitation

3.3.2.1 - Court terme

La Prise de notes en cours de passe (tops chronos et comptage des avions vus et non vus) a permis un débriefing <<à chaud>> avec les pilotes (toutes les 15 min. environ) en leur donnant des informations de performances pour étayer et confronter leur point de vue.

Un débriefing plus complet a été réalisé avec le plus grand nombre possible des pilotes évaluateurs afin de dégager les avis prépondérants.

3.3.2.2 - Temps différé :

A partir des trajectoires du leader et de la cabine, une analyse fine a pu être menée pour déterminer les temps de rejointe de place, les éventuels overshoots, et les écarts sur manœuvre du leader.

Une analyse statistique a permis d'accéder aux entités suivantes : écarts maximaux et moyens sur évolution du leader, pourcentage de temps de tenue de place, et temps de rejointe de la place en fonction de la distance initiale.

Rassemblement :

Le tracé des points mesurés (temps entre le ` top début de guidage' et l'instant où la place est rejointe de manière stable) permet de dégager par une linéarisation la tendance. Le temps varie en fonction de la distance; d'après la loi choisie, cette variation doit être approchable de manière linéaire avec une bonne représentation. On détermine en extrapolant jusqu'aux distances nulles un temps ` talon' en dessous duquel on ne peut pas raisonnablement descendre pour garantir une mise en place effective avant le début de passe. Ce temps est la marge que devra s'offrir le guideur pour s'assurer que tous auront eu le temps de rejoindre leur place (Annexe 4).

<u>Remarques</u> : les temps de rejointe relevés font référence à l'instant où le seuil des 50 m a été atteint. Les temps <<talon>> présentés sont déterminés pour une distance initiale de 500 m.

Tenue de place après rassemblement :

Deux types de statistiques sont effectués : sur les écarts maximaux en distance d'une part, et ensuite sur le temps de présence en place sur une passe standard.

Les **écarts maximaux** observés sont corrélés avec les altérations de cap du leader, les interfaces et les retards de la chaîne de transmission. Les statistiques se présentent sous la forme de pourcentages de réussite (écart max. inférieur aux limites) sur les cas rencontrés. Dans les deux cas génériques, petites évolutions et grands virages de présentation, les temps de rejointe de la place nominale (carré de 50 m) est déterminé : c'est la durée en dessous de laquelle on trouve 90% des points observés (Annexe 5).

La **tenue temporelle** permet d'appréhender les pourcentages de temps passé dans des secteurs de position représentatifs de précisions choisies. Les enregistrements sont la succession de points distants en temps de 80 ms environ. Le comptage des <<populations>> de points constitue une intégration échantillonnée des temps recherchés. Les résultats sont présentés sous forme d'histogrammes donnant les pourcentages de temps en place selon la classe de précision et l'amplitude des évolutions du leader (Annexe 6).

Les classes de précision ont été définies en distinguant les petites et les grandes évolutions, conformément aux objectifs fixés :

<u>Petites altérations de cap</u> :

	Retrait	Ecartement
Classe 1 dite nominale ou contractuelle	50 m	50 m
Classe 2	50 m	100 m
Classe 3	100 m	200 m

Parmi les points, les évolutions inférieures à 6° ont été extraites pour distinguer petites et très petites évolutions.

<u>Grands visages (90° et 180° à inclinaison 45°)</u> :

La distance nominale-avion est prise en compte car elle conditionne des aspects de sécurité liés à l'anti-abordage au sein de la patrouille.

Classe A : D ≤300 m   **Classe B** : D ≤500 m

5. RESULTATS

5.1 - Performances

Ce paragraphe résume les résultats obtenus en trajectographie, indépendamment des avis pilotes.

5.1.1 - Rassemblement

On observe que le temps de rassemblement est fini, ce qui veut dire que l'objectif n'est pas loin. Par ailleurs, pour toutes les interfaces, ce qui se conçoit à l'examen de la définition de la loi de guidage, il apparaît un temps <<talon>> en dessous duquel il semble impossible de descendre sans changer les gains. Ensuite, le temps augmente de façon quasi linéaire avec la distance initiale. On retrouve la saturation en vitesse de la loi.

Les trois interfaces visuelles ont un comportement similaire, par le fait que la nominale est toujours atteinte.

En revanche, l'Audio ne présente pas la même performance : on confirme sur les enregistrements la marque faite <<à chaud>> sur l'Audio, à savoir que la performance en l'état est plus de classe 2 que de classe 1. En effet, en prenant des critères de classe 2 pour la détermination du temps de rejointe, on retrouve un comportement similaire à celui des autres interfaces en classe 1. Cela est dû essentiellement à l'échantillonnage des ordres et aux seuils appliqués sur les caps de consigne (2°).

En faisant l'hypothèse qu'un pilote, à la main ou en poursuite (Cf. plus loin), peut se maintenir en place pendant les virages de présentations à moins de 500 m de sa place nominale, les temps de rassemblement à prendre en compte pour le guidage avant le début de passe sont :

VTH	VTB	IC	AUDIO
60 sec	60 sec	80 sec	100 s (classe 2)

Notons une progression plus forte du temps de rejointe avec la distance pour les VTH et VTB, confirmant ainsi leur sensibilité.

Une minute est un temps tout à fait honorable en regard à ce qu'il faut compter pour le même résultat en phonie classique.

En grossissant le coefficient d'accélération, transformant un écart de vitesse en accélération de consigne, il est possible de rendre la loi plus

nerveuse au distances intermédiaires et par là gagner sans doute une dizaine de secondes, surtout pour l'IC.

5.1.2 - tenue de place

5.1.2.1 - Petites évolutions

La définition même de la loi apparaît dans la dissymétrie entre le retrait et l'écartement pris sur une évolution du leader. En effet la position nominale est définie par rapport à une direction indépendante du cap du leader, permettant de découpler au premier ordre la tenue de place des oscillations de cap du leader.

Il apparaît donc :

- ◊ un <<classement>> global de performance brute, via le tableau statistique des écarts de position : VTH, VTB, IC et AUDIO.
- ◊ que la tenue longitudinale est plus performante que la tenue latérale, l'interface la plus marquée étant l'audio. Pour celle-ci en effet une évolution du leader peut être masquée au pilote pendant quelques secondes en raison des intervalles minimums entre messages.
- ◊ que la très bonne performance globale de la VTH qui représente sans doute le mieux la loi de collision choisie.
- ◊ que la VTB donne le meilleur chiffre en latéral, ce qui est dû à la présentation de la situation horizontale permettant de détecter des mouvements de la nominale avant de voir les ordres bouger de manière significative. La tenue du retrait s'en trouve pénalisée sur la VTB par rapport à la VTH par une nette différence de sensibilité sur l'affichage de la pente potentielle.

Les temps de retour en place (classe 1) donnent une idée, sachant que les virages de 5° et 10° durent respectivement environ 15 et 20 secondes, du temps d'excursion lors de la plage spécifiée. C'est l'objet des planches qui présentent le **pourcentage de temps en place** selon la classe de précision (Cf.§ Méthode pour la finition des classes).

L'observation de ces planches amène les remarques suivantes :

- ◊ L'audio passe la barre des 50% pour la classe 2, confirmant l'observation faite pour les rassemblements. Il faut donc retoucher cette interface pour prétendre atteindre la classe 1.
- ◊ Si les écarts maximaux donnaient la VTB plus performante que l'IC, en revanche on s'aperçoit que cette dernière est meilleure en temps moyen de présence pour toutes les classes : cela est dû là encore à un meilleur réglage des gains pour l'affichage des ordres en cabine pour l'IC que pour la VTB.
- ◊ Enfin, la VTH, en limitant les évolutions du leader à 5° environ, affiche une performance de 100%.

Effet de retard :

Les effets du retard sur la tenue de place sont à considérer avec prudence : en effet le nombre de points observé reste réduit, notamment pour le retard de 2 secondes (2 points); par ailleurs la dispersion de ces points est telle qu'une recherche de tendance est peu représentative.

A ce stade de l'étude, on peut dire sans surprise que la performance diminue avec le retard de transmission, qu'un seuil semble atteint avec environ 1.5 secondes.

Enfin, en diminuant les exigences sur la précision, cet effet s'atténue : en effet les performances en classe 3 est identique et excellente jusqu'à 2 secondes de retard.

5.1.2.2 - Virages

La planche des écarts maximums sur évolution mets en évidence les qualité des interfaces, et la capacité de rassemblement en manœuvre de la loi.

La VTB, par sa situation horizontale, permet de se rendre compte immédiatement de l'ampleur de son écart et par là de stopper l'éloignement. C'est là qu'on observe les plus faibles écarts. C'est la VTB qui permet un rassemblement en fin de 180°.

La VTH se diffère de l'IC par sa sensibilité aux ordres permettant de résorber plus vite le retard, notamment en vitesse.

Ces évolutions montrent que des écarts importants sont possibles, et qu'il conviendra de préciser ces performances et de définir une distance minimale leader-nominale avant de demander une telle évolution <<aveugle>> à un plastron.

5.2 - Aspects de sécurité

5.2.1 Surveillance du ciel - Disponibilité

La surveillance de l'environnement extérieur s'est avérée très efficace en VTH et IC, nettement moins en VTB ou Audio (NB : Audio en cabine classique ; Audio + VTH brute se résume à la VTH).

Le résultat n'a rien d'étonnant pour la VTH ; en revanche, il peut l'être plus pour la VTB : celle-ci est donc plus accaparante que l'IC. Une des raison est que les informations de guidage, en IC, s'insèrent dans un circuit visuel classique de pilotage, éduqué pour garder du temps pour l'extérieur.

5.2.2 Instabilité - Ecart excessifs

Deux inversions ont été observées faisant faire demi tour face au leader! Il y a là un problème de sécurité, lié à une instabilité dans la loi. Même si les deux cas ont eu lieu dans des configurations limites (Vi < 200 kt et 1500 m en avant de la nominale) une attention particulière doit être portée sur ces problèmes. Notons toutefois qu'il n'a pas été possible de reproduire ces événements.

5.3 - Observations pilotes

La VTH a été jugée très agréable et sûre; toutefois, l'absence d'information sur la place de la nominale empêche le pilote de savoir à quel stade du rassemblement il se trouve, ou quelle marge de manœuvre il lui reste avant de sortir de sa place. La charge de travail s'en trouve accrue.

La VTB est devenue confortable grâce au changement de définition de la situation tactique. Par ailleurs, elle est trop attractive, de sorte qu'elle accapare trop l'attention du pilote dans la cabine. Le pilotage est assez difficile en tangage en VTB; toutefois la contribution du simulateur est importante dans ce domaine.

L'adéquation de l'IC dépendra beaucoup de la position des instruments dans la cabine. Une mauvaise adaptation rendra l'interface inopérationnelle, voire dangereuse.

L'ajout d'une situation horizontale mixte ainsi réalisée (Cf. annexe) est très attrayante. Cette dernière solution reste celle préférée des pilotes dans leur ensemble, hormis la VTH dont on sait qu'elle pourra difficilement équiper le MIIIR.

5. METHODE D'ESSAIS EN VOL

Le but de ces essais en vol était de démontrer la faisabilité de ce Guidage Autonome et de confirmer les résultats obtenus en simulation. La loi de pilotage mise au point en simulateur a été montée sur un ABE Mystère XX. Un avion leader est simulé à bord et une nominale est définie à volonté. La loi de pilotage peut être modifiée en temps réel en agissant sur le coefficient k_0 et sur le coefficient K_2. La modification de la saturation de la Vr est aussi possible au sol mais n'a pas été faite dans cette tranche d'essais. La première interface choisie a été le HDD. Etait présenté en cabine une recopie vidéo d'un écran situé en soute arrière.

Les limitations étaient donc les suivantes :

◊ Loi de guidage optimisée pour un Mirage 2000 et non un MXX, aux commandes plus lourdes et aux réactions moins vives.

◊ Médiocre qualité du HDD, mal positionné dans la cabine et objet nombreux reflets du soleil.

◊ Retard de transmission de données non simulé.

La méthode d'essais a consisté à dissocier le latéral du longitudinal en jouant sur le coefficient k_0 dans un premier temps et sur le coefficient K_2 dans un deuxième temps (voir Annexe, loi de pilotage).

◊ Rejointe de la nominale placée 1000 m derrière l'avion, 250kt, avec coefficient K2 = 0.08, K2 = 0.04 et K2= 0.20

◊ Rejointe de la nominale placée à gauche ou à droite 1000m en FMD, 250kt, avec coefficient k_0 = 0.04, k_0 = 0.02 et k_0 = 0.08

◊ Tenue de place, nominale stable à 250 kt, pendant 5 min pour évaluation de la charge de travail.

◊ Tenue de place, altérations de cap de la nominale de +/-5° pour comparaison des performances obtenues avec celles réalisées au simulateur.

◊ Accélérations/décélérations de la nominale.

◊ Rejointe de la nominale stable, départ FMO 2Nm avec les coefficients déterminés en simulation.

◊ Virage 180° $\phi = 30°$.

◊ Virage 180° $\phi = 45°$.

6. RESULTATS D'ESSAIS EN VOL

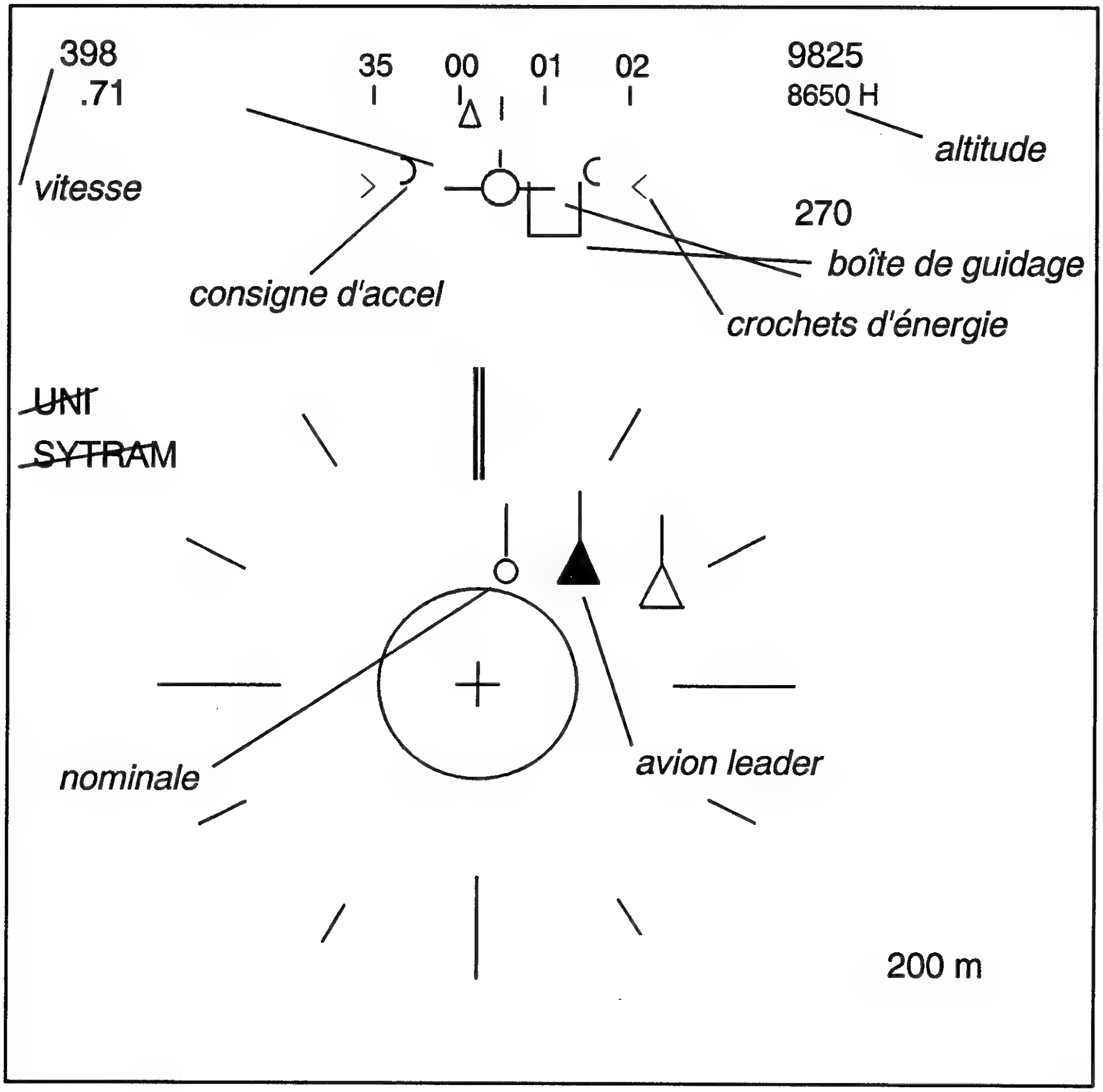
Les résultats des essais en vol ont prouvé la faisabilité du projet et ont permis de montrer que les résultats obtenus en vol sont assez proches de ceux obtenus dans la simulation. L'étude de ces résultats n'ont pas été aussi poussés car tel n'était

pas le but de ces vols. Pour des virages de 90° et 180°, les résultats sont toujours demeurés de la classe A, ce qui assure des temps de retour en place conformes à ceux obtenus en simulation. En tenue de place lors de petites variations de cap, les résultats sont de la classe 1, avec une charge de travail plus faible que celle observée au simulateur. En revanche, la loi optimisée pour un modèle plus ou moins douteux du Mirage 2000 devra être optimisée pour chaque type d'avion, en fonction de ses capacités propres d'accélération et de décélération ainsi qu'en fonction de ses caractéristiques de pilotage en roulis. La Vr devra être plus élevée afin de gagner quelques secondes au cours de la rejointe. Le coefficient k_0 initial un peu faible donnait une réponse trop molle avec quelques overshoots. *Mais un point faible n'a pas pu être évalué : l'influence du retard introduit par les délais de transmissions.*

Une nouvelle tranche d'essais sera faite prochainement sur un αJET dont la place arrière sera équipée pour l'expérimentateur, le nouvel écran à cristaux liquides pour le HDD étant en place avant. L'interface HUD devra aussi être expérimentée, probablement sur M XX, déjà équipé d'un HUD de Mirage 2000.

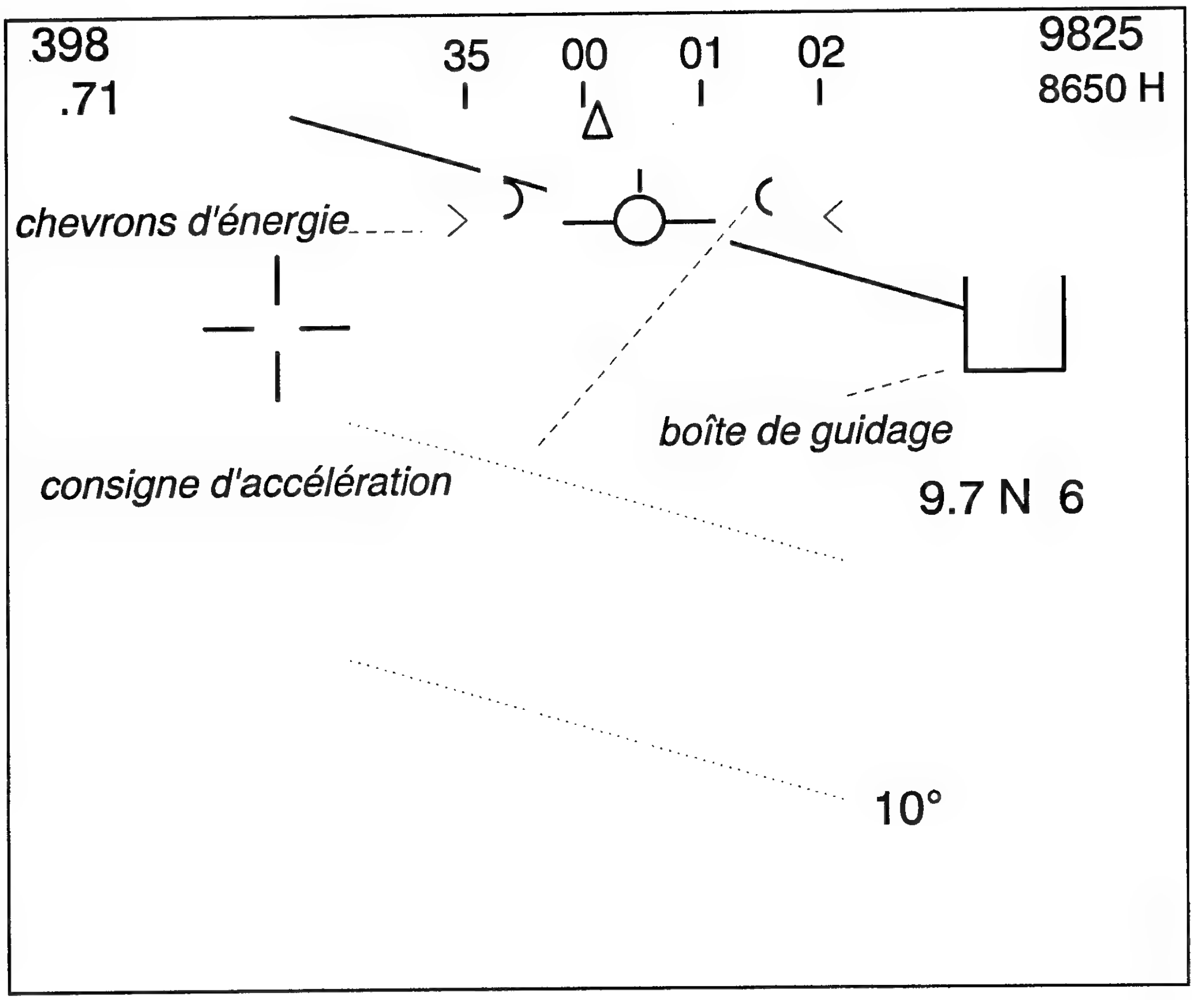
ANNEXE 1

HDD


398
.71
vitesse
35
00
01
02
9825
8650 H
altitude
270
boîte de guidage
consigne d'accel
crochets d'énergie
~~UNI~~
~~SYTRAM~~
nominale
avion leader
200 m

ANNEXE 2

HUD


398
.71
35
00
01
02
9825
8650 H
chevrons d'énergie
boîte de guidage
consigne d'accélération
9.7 N 6
10°

ANNEXE 3

LOI DE NAVIGATION

ELABORATION DE LA VITESSE ET DE L'ACCELERATION DE CONSIGNE

LOI BRUTE: (collision pure : fermeture du triangle des vitesses)

$\frac{\partial D}{\partial t} = ko \,.\, D \Rightarrow$ consignes brutes: R_{co} route de consigne

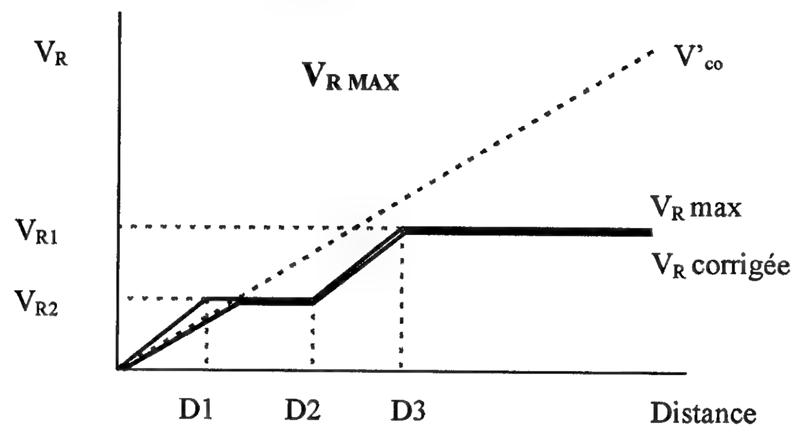
V_{co} vitesse sol de consigne

CORRECTIONS SUR Vco :

1 - amplification de l'effet de vitesse :

$$V'_{co} = V_{NOM} + K_v \,.\, (V_{co} - V_{NOM})$$

2 - Saturation en valeur absolue de la différence de vitesse :



Selon le secteur, on obtient la courbe V'co bleue; la différence $|V_{NOM}-V'_{co}|$ est saturée par la courbe rouge V_{RMAX}; on obtient la $V_{R,corrigée}$ (verte);

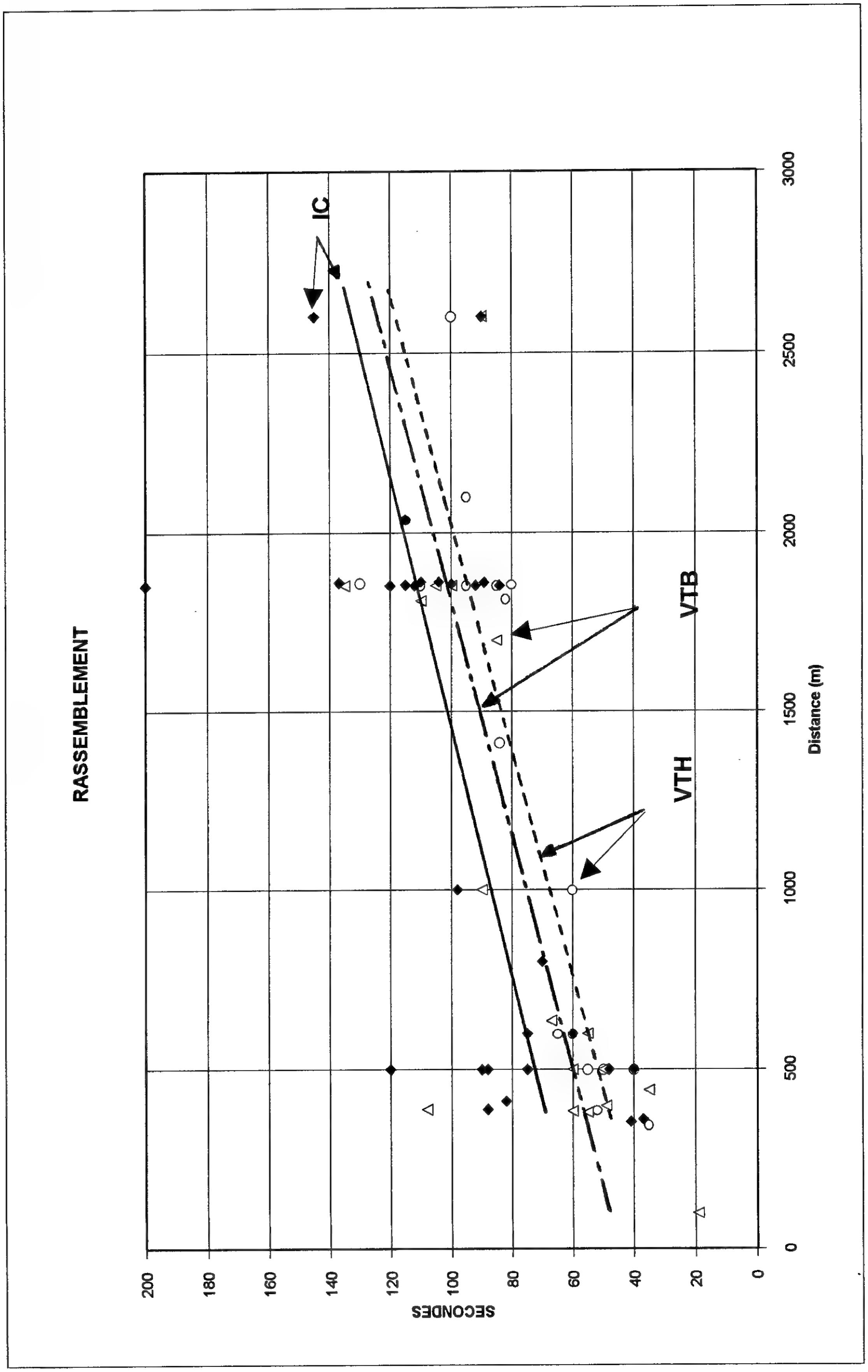
$\Rightarrow$ $Vsc = V_{NOM} \pm V_{R,corrigée}$ (Vsc utilisée directement en Audio)

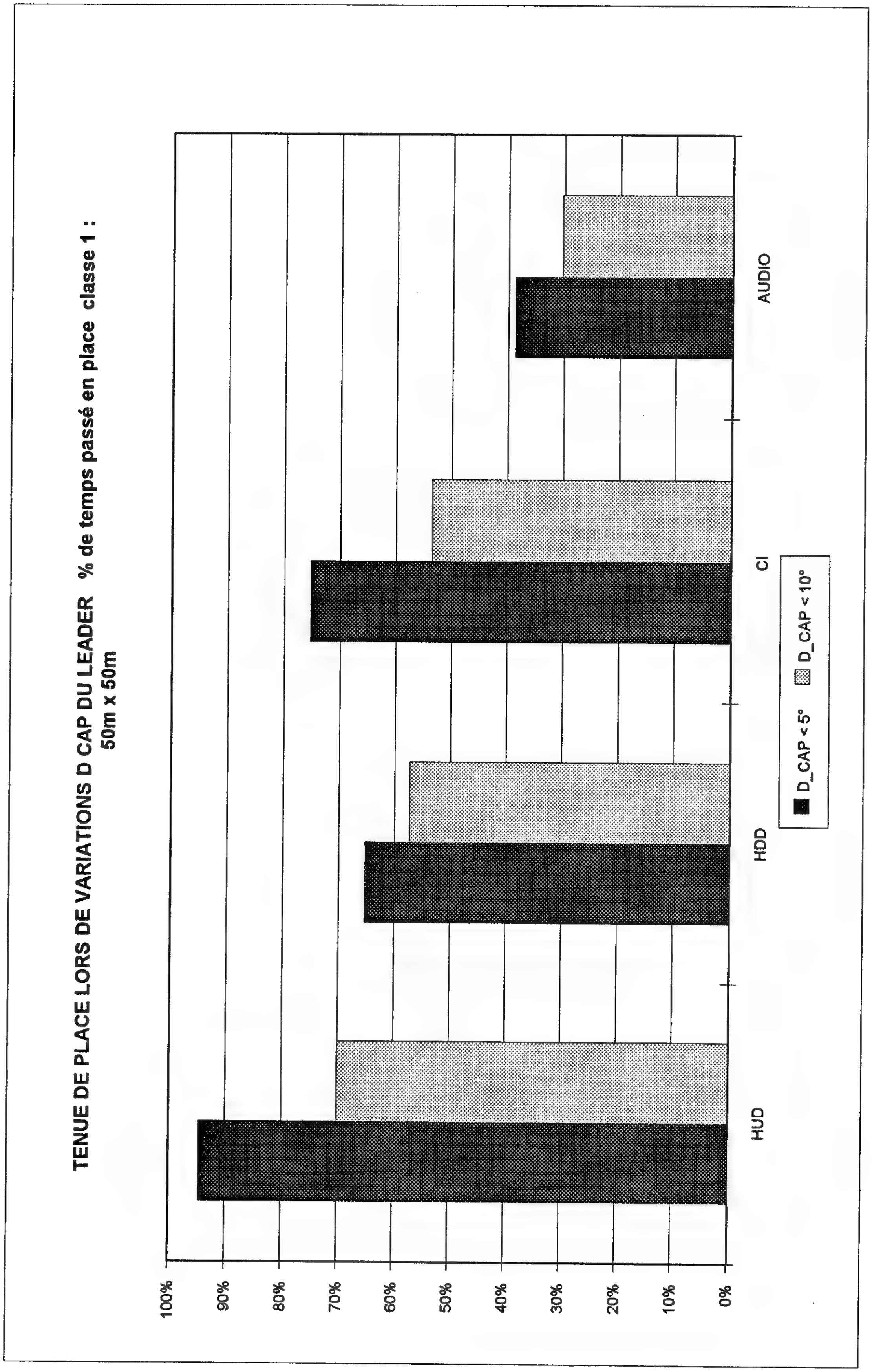
CALCUL DE L'ACCELERATION DE CONSIGNE :

$\gamma_c = K_2 \,.\, (Vsc - Vsa)$ Vsc vitesse sol de consigne
Vsa vitesse sol actuelle

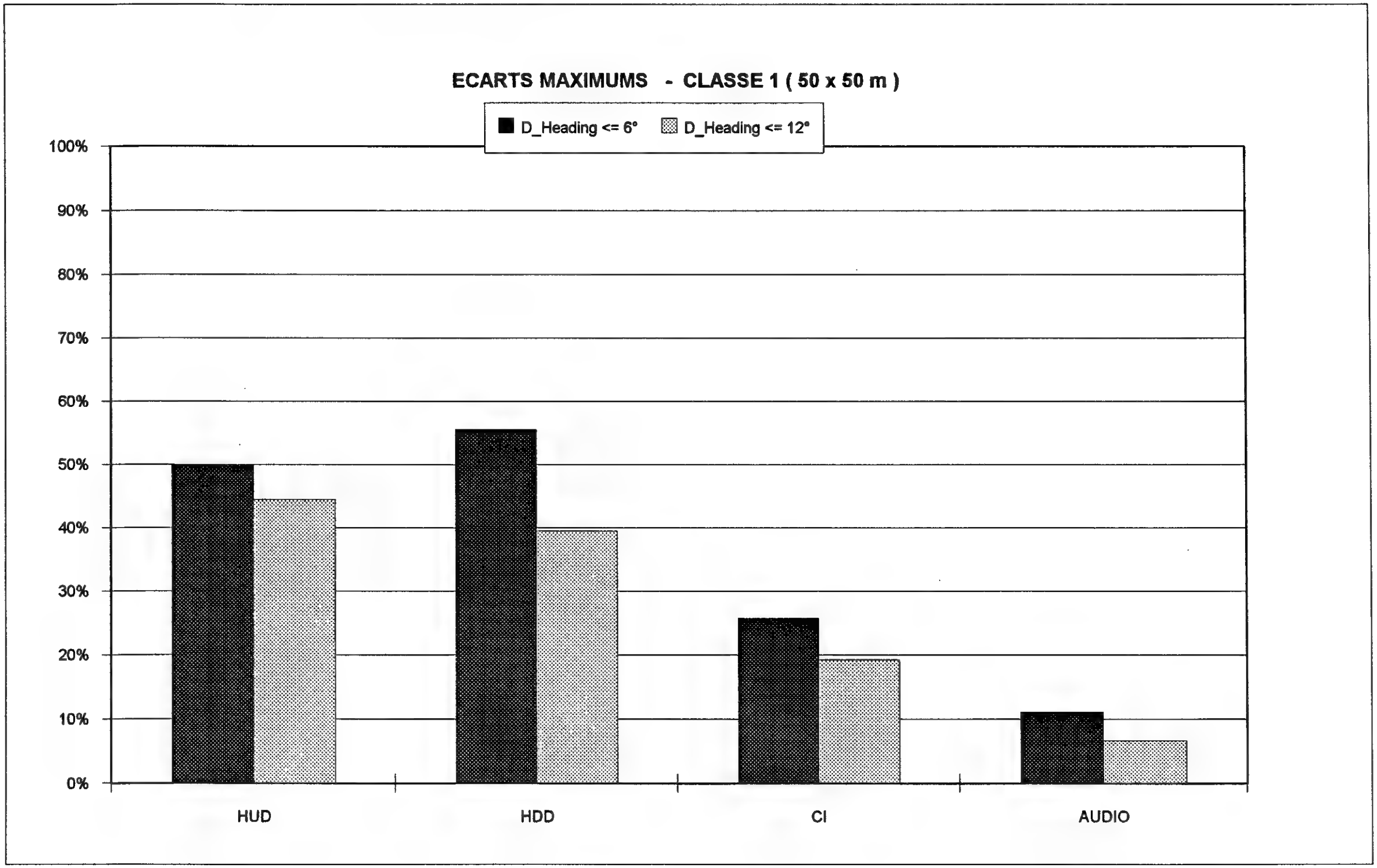
COEFFICIENTS ESSAYES :

Ko	Kv	D1	D2	D3	VR1	VR2	K2
0.04	2	50 m	300 m	2000 m	5 m/s	25 m/s	0.04


RASSEMBLEMENT
SECONDES
Distance (m)
IC
VTB
VTH
0
20
40
60
80
100
120
140
160
180
200
0
500
1000
1500
2000
2500
3000



TENUE DE PLACE LORS DE VARIATIONS D CAP DU LEADER % de temps passé en place classe 1 :
50m x 50m
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
HUD
HDD
CI
AUDIO
D_CAP < 5°
D_CAP < 10°


ECARTS MAXIMUMS - CLASSE 1 (50 x 50 m)
D_Heading <= 6°
D_Heading <= 12°
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
HUD
HDD
CI
AUDIO

European Flight Experiments on 4-Dimensional Approach and Landing with the CASA 212 Aviocar Aircraft.

by

J.R.C. Azinheira (IST), A.A. Fonseca (IST),
Instituto Superior Tecnico, Av. Rovisco Pais, 1096 Lisboa, Portugal

C. Garcia Avello (EUROCONTROL) and S. Swierstra (EUROCONTROL)
rue de la Fusée 96, 1130 Brussels, Belgium

1. INTRODUCTION

Over the years a continuing increase in demand for air travel was observed that always surpassed the highest estimates. The capacity limit of the major airports constitutes one of the bottlenecks in the expansion of air transport.

In order to maintain a competitive edge, air carriers use aircraft types that offer optimum economy on the routes they fly. In a typical hub operation, this results in a mixture of jet, turbo-prop and prop aircraft, each with a different operational speed range.

Today for the main airports, the runway constitutes a major bottleneck. Accordingly the optimisation of the capacity of an airport becomes a very complex task when the stream of inbound aircraft consists of a mixture of aircraft types.

The introduction of automated tools to enhance the efficiency of the air traffic controllers is one of the targets of the EATCHIP programme to improve the overall quality of the air traffic control services provided.

Research programmes have led to the development of such tools, in particular to assist the air traffic controllers with the problem of optimum Arrivals Management. Meanwhile these tools have been tested and initially validated in simulation environments.

The requirement existed to test and demonstrate algorithms developed using a real aircraft, initially in an isolated, well-controlled flight environment.

This has led the EUROCONTROL Agency (EHQ, Brussels) and the Instituto Superior Tecnico (IST, Lisbon) to organise in close co-operation with Aeroportos e Navegacao Aerea (ANA, Lisbon) and the Forca Aerea Portuguesa (FAP, Sintra, Ovar and Montijo) a live exercise to investigate the feasibility and performance of such a tool (Ref 1).

This report describes the flight trials and some of the conclusions drawn. The references at the end of this text give a detail explanation of the different components that were used to perform these trials.

Figure 1 shows a picture of the CASA 212 aviocar fitted with its test equipment and probes.

2. OBJECTIVES

The experiments aimed to :

- Validate the combination of ATC tools integrated in the simulation environment using a realistic ATM scenario. Exercises of this type ensure that the results obtained from subsequent simulations and demonstrations can be assessed efficiently. To this effect extensive validation and calibration of the simulation environment in conditions which are as realistic as possible, are a prerequisite.
- Assess the efficiency of control procedures, methods and techniques to manage a complex mix of fast and slow traffic.
- Investigate the interaction between SYSCO Level 1 co-ordination procedures and the advisories generated by an advanced Arrivals Management tool.
- Assess the predictability of slow aircraft.
- Assess the impact of such automated Air Traffic Management tools on the flight execution both in terms of flight operating cost and cockpit workload.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

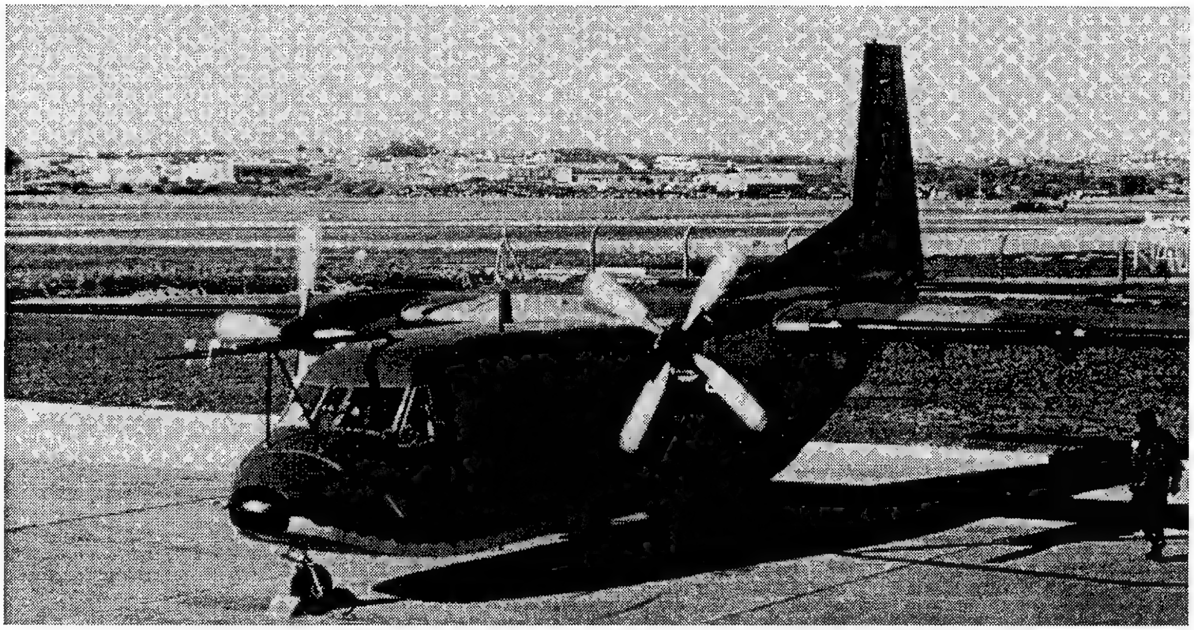


Figure 1 : View of the CASA 212 Aviocar aircraft

- Assess the impact of such tools on the management of traffic in the simulated airspace.

- Assess the impact of such tools on controller workload.

- Demonstrate the advantages of EATCHIP Phase III tools in support of the specification activities currently in progress within ANA.

3. ATC SIMULATION ENVIRONMENT

The experiments comprised the management of a stream of aircraft inbound to Lisbon International airport in a peak traffic period. The traffic sample consisted of the CASA 212 in real flight, integrated in a stream of simulated aircraft inbound to Lisbon.

The ATC system consisted of the STANS platform (Simulation for a Total Air Navigation System, Ref 2) that has been earlier used for similar experiments (Ref. 3)

STANS is a real time ATC simulation platform that facilitates the integration of real external air data in a simulated ATC environment. It comprises controller working positions that are based on the operational requirements for the EATCHIP Phase III system generation (Ref 4).

4. ORGANISATION OF THE EXPERIMENTS

The EUROCONTROL Agency provided the simulation environment, the associated technical support and had the overall responsibility for project management

The IST had the responsibility of organising the exercises on site, i.e., develop the required data processing tools to extract position data from the SSR, organise suitable VHF radio communications arrange the installation of the telemetry and recording equipment for flight tests and co-ordinate the schedules for the aircraft with FAP.

FAP provided the CASA 212 Aviocar with pilots, the air base and airspace for the trials.

All the support to prepare the technical aspects of these experiments was also provided by the FAP entities involved, at the Air Force Head Quarters and at Ovar, Sintra and Montijo Air Bases. FAP also provided an Air Traffic Controller.

ANA was responsible for providing operational support during the process of defining the operational scenario for the trials and for making available controllers for the live exercises.

5 THE GEOGRAPHICAL ENVIRONMENT

The exercises have taken place at the FAP/NATO military air base of Ovar, 20 nm south of Oporto.

The airfield is equipped with a set of radar equipment for Ground Control Approach (GCA) including a Secondary Surveillance Radar (SSR) and a Precision Approach Radar (PAR) - the latter was to be used to allow the CASA 212 to fly ILS like approaches.

The military restricted airspace, close to the runway, had an upper altitude limit of 5500 feet with the possibility of going above after a clearance given by Oporto civil controllers. This upper limit was reduced to 2000 feet twice during the trials due to Oporto inbound traffic. However, to the West, over the sea, there was no altitude restriction thereby making it possible to simulate realistic inbound flights starting at 10000 feet.

The Ovar Tacan has been used to define the route of the CASA 212 in such a way that it could fly a realistic flight plan before receiving the radar vectoring instructions from the approach controller.

6. THE OPERATIONAL ENVIRONMENT

For the realism of the exercises the ATC environment that exists for the Lisbon international airport was simulated. This had the advantage that the controllers were already familiar with this environment and that no additional ATC procedures needed to be developed.

The 36 runway of OVAR air base was used to simulate the 35 runway of Lisbon. The radar positions of the CASA 212 as observed by the Ovar SSR system were translated accordingly so that it appeared that the aircraft was operated in the area of Lisbon.

The airspace was devided into two sectors, the standard Lisbon TMA and a feeding sector encapsulating all the adjacent sectors.

Both crossing runways of the airport, 03 and 35, where used for landings during the trials and were considered as dependent. Takeoffs were concentrated on runway 03.

The traffic samples included inbound and outbound traffic as well as some VFR flights for the realism of the exercises. They include normal scheduled flights from Lisbon airport.

The number of aircraft in the traffic samples varies from 10 to 14 for a period of approximately half an hour.

The flows of traffic simulated were similar to the major ones of Lisbon in number of aircraft and in direction of major streams.

In order to keep a sufficient level of traffic in both sectors during the whole extent of a trial exercise, outbound and inbound flights could be activated both at predefined moments and at the simulation operator request to cope with the real time aspect of the trials and never making two successive trials to look identical.

The CASA 212 aircraft was inserted into the jet aircraft inbound sequence when starting its inbound flight segment from FL100 and some 30 nm away from the runway.

The civil controllers of Oporto airport had the possibility to restrict the upper limit of the military reserved airspace at any moment in time due to their civil traffic.

During the exercises overall air traffic safety was ensured by the military Ground Control Approach (GCA) and control tower of the airfield.

7. ATC FUNCTIONS AVAILABLE

The basic Flight Data Processing System (FDPS) was enhanced with an advanced, multi-sector arrivals management tool. The main objectives of the experiments were to investigate how such a tool could help in improving traffic handling capabilities in a mixed speed traffic situation. This tool is based on the Zone Of Convergence (ZOC) concept (Ref. 5) and aims at continuously providing the controllers, across several sectors, with the "best next clearance" to maintain a safe and efficient landing stream. It integrates aircraft speed capabilities and wind forecasts into its trajectory calculation process, to accurately predict the future progress of the aircraft. It uses this information to efficiently sequence the aircraft and provide the controller with the information necessary to build the ATC clearances required in the sequencing and metering process. It is always up to the controller to send the ATC clearance.

Additional advanced functionality was provided to the controllers to handle inter-sector co-ordination

in the form of the electronic Co-ordination And Transfer (CAT/SYSCO) protocol.

The CAT/SYSCO functionality allows the controller of two adjacent sectors to negotiate hand-over conditions (e.g., altitude, airspeed and aircraft heading) via mouse inputs directly through the data representation in the radar identification label on the radar screen.

The controller interaction with the ATM system was done exclusively via the mouse and no paper information was used.

Figure 2 gives a view of the ODID concept based TMA Controller Working position with the traffic simulated during one of the flight trials. The label FAF212 represents the CASA real aircraft.

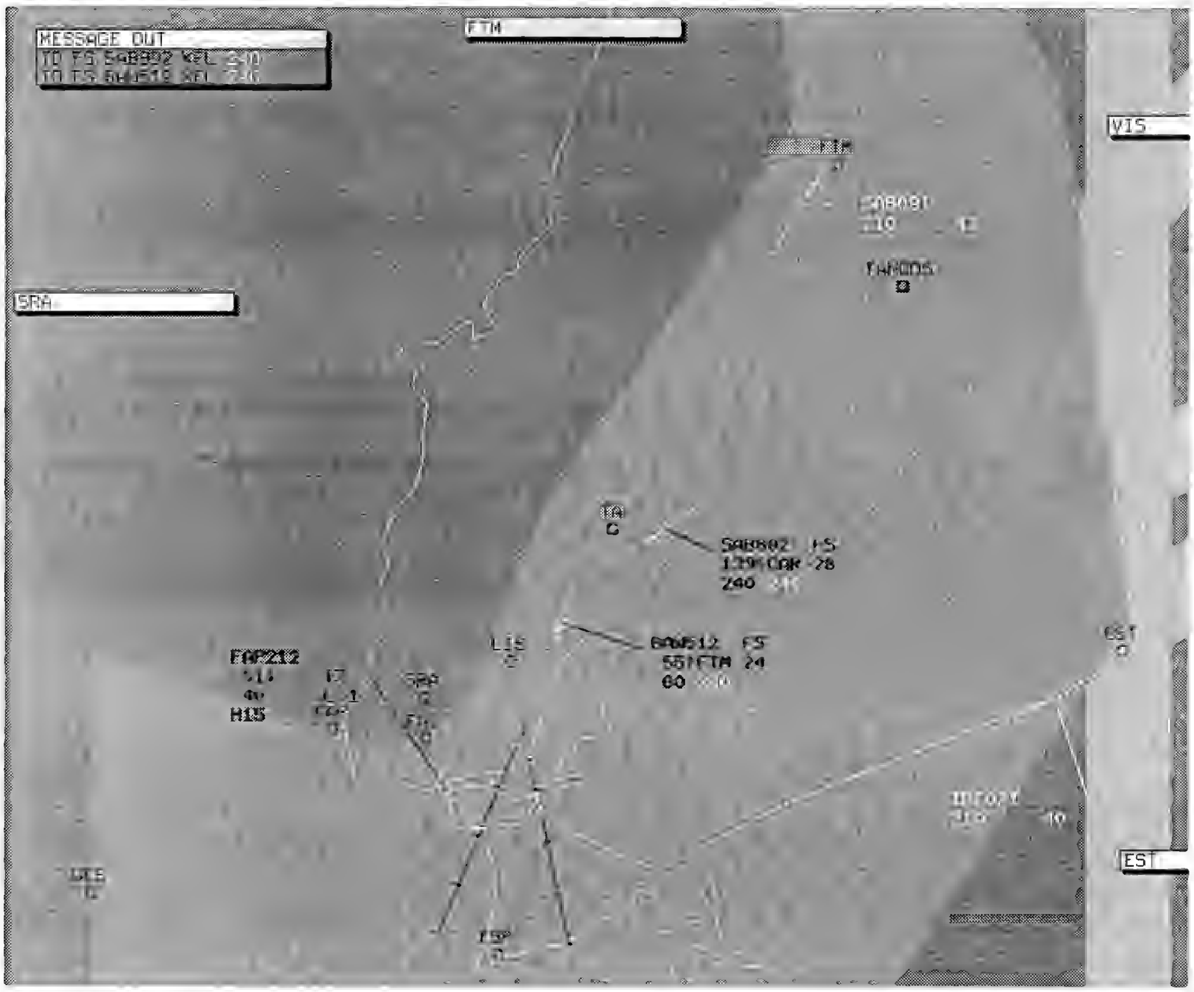


Figure 2 : The ODID concept based Controller Working Position.

8. TECHNICAL DESCRIPTION

8.1 System architecture

The computer system for the trials consisted of three UNIX workstations interconnected by a LAN.

One for each controller working position and one running the simulation. A 21 inch colour screen was attached to each of the workstations.

8.2 Communications

Two physical links with the live system were required to be able to perform the trials:

- a link with the SSR providing latitude, longitude and altitude position data.
- a VHF link to communicate with the CASA 212.

For safety reasons a telephone link with the military Ground Control Unit at the air base was provided. This unit co-ordinated the possible clearances directly with the Oporto airport.

Figure 3 represents the system architecture during the trials and shows the components and their links.

9. THE SSR TO STANS DATALINK.

The secondary radar data accessible at the output of the radar HDLC interface card were read and filtered by a data extraction interface, in order to supply the STANS system with the flying CASA 212 data.

The data extraction interface, designed by IST, had been previously tested at the GCA of Montijo FAP Air Base in July 1994 and at the GCA of Ovar in October 1994 as the same SSR data was available at both air bases.

At the beginning of these trials the radar-to-STANS connection was checked and an helicopter based at Ovar Air Field was used as a target to calibrate the simulation localisation in accordance with radar data such that the OVAR runway touch down point coincides with Lisbon runway airport.

The available output from the secondary radar unit was an HDLC TTL bitstream at 2400 baud rate with packets of information containing all the secondary data of detected aircraft, namely the range and azimuth of the targets, plus the altitude in the case of mode C validated data.

The data extraction interface had to process the SSR output and compose the serial input for STANS equipment.

The following tasks were performed in real time by this interface:

- electrical filtering of the secondary radar output signal
- bit synchronisation
- HDLC frame synchronisation
- reading of all targeted aircraft data
- extraction of Aviocar individual data, based on SSR/IFF code
- conversion of Aviocar data from range/azimuth (centred on GCA location at 40°55'07"N, 08°38'33"W) to latitude/longitude co-ordinates,
- shift of co-ordinates from Ovar area to Lisbon area,
  data formatting according to ASCII EUROCONTROL radar input format, namely indicating time, latitude, longitude and altitude
- output Aviocar data through RS232 serial port

Hence the STANS system was provided with a 28 characters long ASCII string at a normal rate of one string per period of 5 seconds, closely synchronous with the radar revolution time.

10. THE AIRCRAFT

The CASA 212 flight test aircraft, a turboprop of the Portuguese Air Force (N/C 16523) was operated by Squadron ESQ401 from Air Base n°1, at Sintra, near Lisbon.

This aircraft is normally used for aerial photography but it has been equipped with a comprehensive set of instrumentation devices and may be rapidly transformed into a Basic Aircraft for Flight Research, in co-ordination with the Aeronautics Laboratory of Instituto Superior Tecnico, for flight trials campaigns (Ref 6).

An IFF transponder and a single antenna allowed tracking of the Aviocar by the secondary radar of the GCA.

For the present trials, no digital data link was installed between the flight test aircraft and the STANS simulation and control stations. The aircraft dynamic parameters and status or settings available

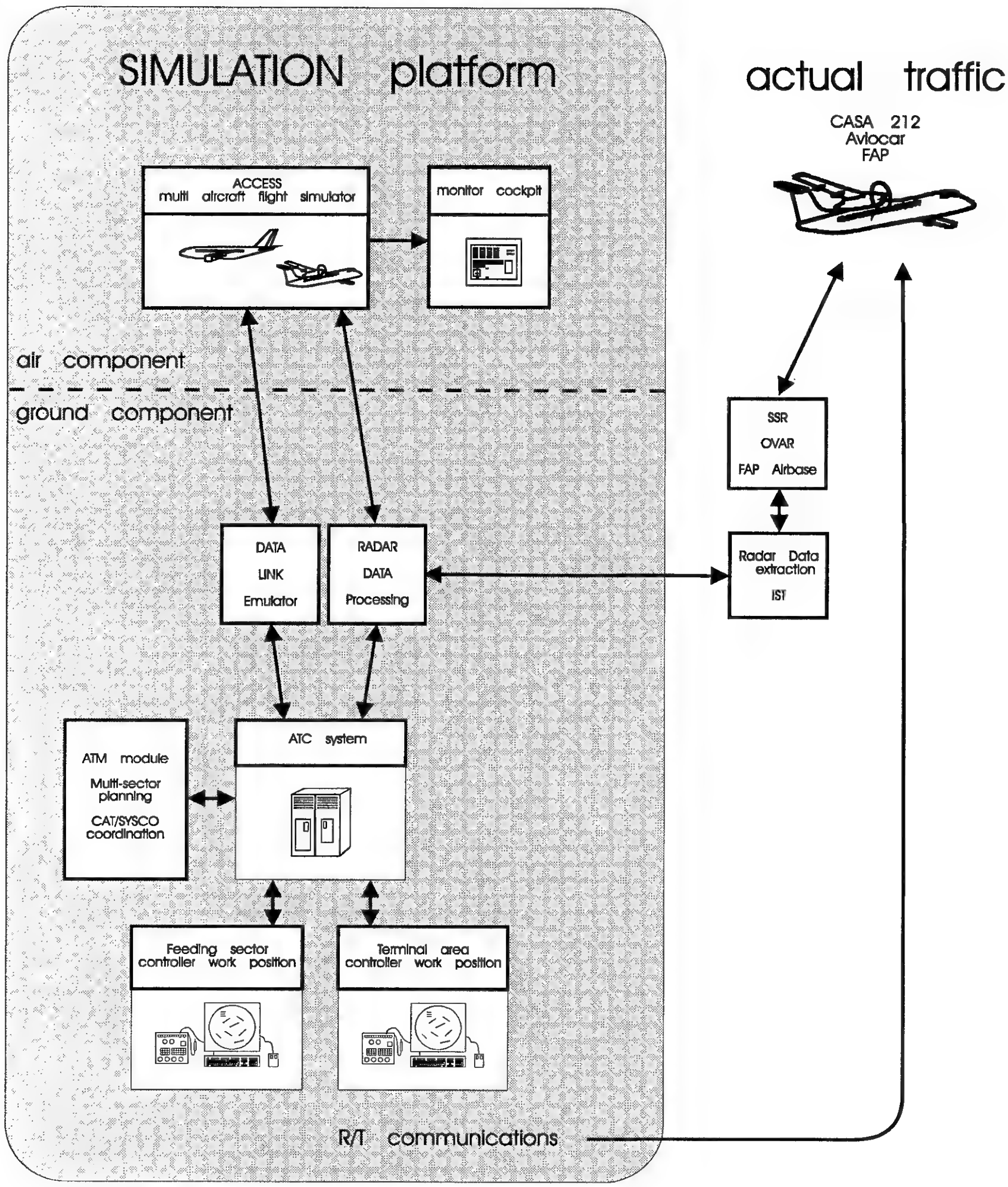


Figure 3: SYSTEM set-up

from the airborne instrumentation were not intended for real time use but only for post-analysis.

The list of the recorded airborne parameters for further analysis on the impact of the ATM procedures investigated is given below.

- time
- barometric altitude
- radio altitude (saturated above 2500 ft)
- true air speed
- indicated air speed
- angle of attack
- flap position
- angular body rates
- linear accelerations
- left and right engine speeds

Data were recorded at 125 kbit/s overall rate, resulting in 316 Hz sampling rate - such a high sampling rate was found not to be necessary and was afterwards reduced to a 1 Hz rate more suitable for trajectory analysis and plotting.

Correlating on-board recorded data with the records of the radar data, allows a precise flight profile evaluation.

11. THE ACTUAL FLIGHT TRIALS

Two days in February 95 were dedicated for live flight trials.

Figure 4 shows the horizontal path whilst Figure 5 gives the vertical profile and the speed profile of one of the CASA 212 aviocar flights.

The first problem encountered was the bad radar visibility of the CASA 212. Due to the Standard Arrival Procedure selected, the last segments of the inbound flight included sharp turns which caused problems due to the fact that the aircraft was equipped with a single antenna.

This problem was partly solved by dynamically tuning the sensitivity of the SSR system during the progress of the flight. This procedure optimised the choice between radar visibility and number of reflections.

Due to the slight difference in the Ovar runway orientation compared to that of Lisbon, some adaptation of the simulated Lisbon airspace organisation had to be performed. As it was only a few degrees, the ANA controller ensured that this did not affect their perception of the aircraft being flying within the Lisbon TMA.

The first run was done with the CASA 212 as the single inbound aircraft to validate all the communications channels and to ensure a safe progress of the aeroplane down to the touch down point.

The number of aeroplanes in the traffic sample was slowly increased up to a total of 14, both inbound and outbound.

The arrivals management tool allowed the control of the position of the CASA 212 in the landing sequence. It was possible to insert the CASA 212 at different positions in the inbound stream to investigate traffic situations of different levels of complexity and decide which sequence of fast-slow aeroplanes gave the optimum landing capacity under the given meteorological conditions.

During these two days of trials, Oporto restricted twice the ceiling because of civil traffic, invalidating the runs performed at that moment in time.

The CAT/SYSCO protocol used for electronic inter-sector co-ordination has been successfully used by the controllers, and the Arrivals Management multi-sector tool has shown its capability of dealing with traffic situations of increasing complexity. It also demonstrated the capabilities of the machine to help the human in sequencing this mixed inbound traffic.

Two different operational scenarios were investigated. The first one proposed to the controller the "best next clearance" up to the moment the aeroplane had to turn to intercept the localizer and the second one stopped advising the controller at the moment the "Turn to Base" message was displayed.

The reason for investigating these two scenarios was that the controllers got the impression of losing some control if the machine is continuously advising them during the whole approach. They also believe, and this is quite probable in most cases, that they could perform as well as the machine when the aircraft are close to the touch down point, especially if the Arrivals Management tool has already helped them in previous sectors to sequence and separate the traffic. However, the large differences in aircraft approach speeds, and especially if there is a large wind component, then they felt that the machine could be of great help by advising them on turn points or speed changes down to the touch down point.

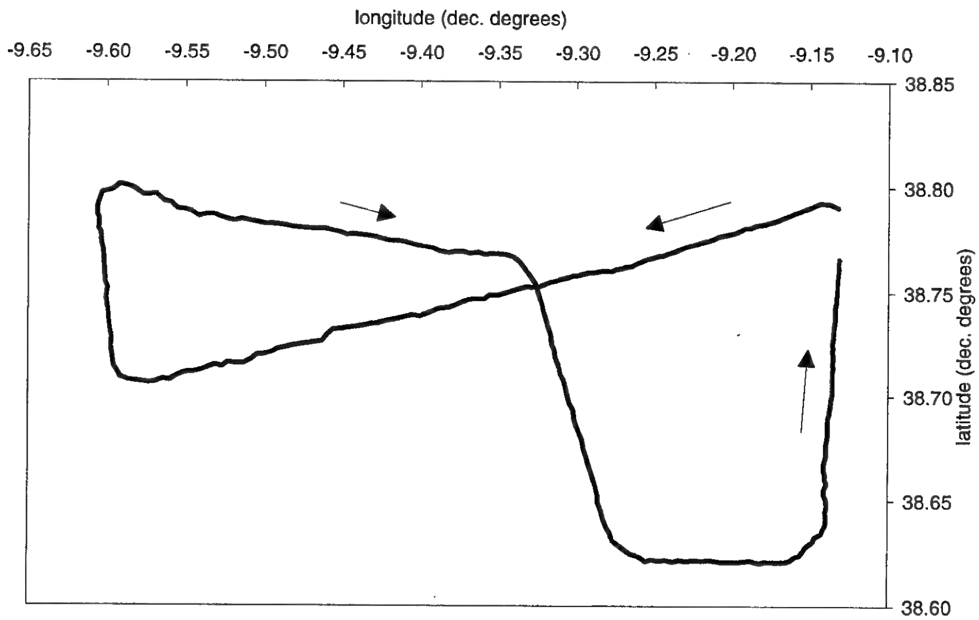


Figure 4 : Aviocar horizontal trajectory example (with coordinates shifted for Lisbon Airport)

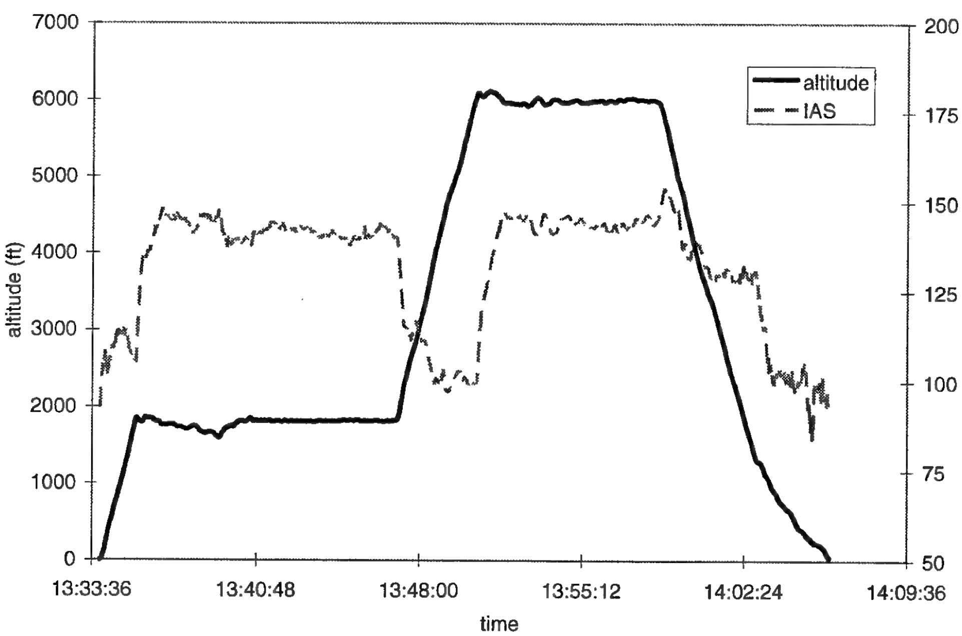


Figure 5 : Aviocar vertical profile and speed example.

12. EXERCISES RESULTS

Despite the relatively small number of runs with the CASA 212 integrated into the simulated traffic that were actually performed during these two days of flight trials, it is still possible to infer some relevant results, which, in accordance with the defined objectives, are mostly expressed in terms of detailed evaluation and validation.

12.1 Validation of the simulation platform and slow traffic prediction

The first result concerns the high level of realism and the flexibility of the simulation platform used to integrate the CASA 212 and the ground equipment tracking the aircraft.

The STANS environment is now mature for such live experiments because as demonstrated during the trials the controllers could not distinguish the real aircraft from the simulated ones.

This is a significant result because it validates the environment used and increases the credibility level of further evaluations to be performed within this environment, even in the situation where all the elements will be simulated.

An other key result was the demonstration of accurate slow traffic prediction. The Aviocar was precisely predicted and guided, along with the simulated jet traffic, requiring no special attention from the controllers.

12.2 Validation of the procedures

The CAT/SYSCO protocol used for electronic inter-sector co-ordination has been successfully used by the controllers, and the Arrivals Management multi-sector tool has shown its capability of dealing with traffic situations of increasing complexity.

It also demonstrated the capabilities of the machine to assist the human in sequencing this complex mixed speed inbound traffic.

12.3 Airborne flight parameters recorded

The ability to record flight parameters on the aircraft as well as on the ground, in conjunction with the possibility of a telemetry link for real time analysis, gave an additional value to such trials.

For example the post-flight profile analysis allowed comparison of the simulated data with the airborne recorded data and therefore validate the simulation credibility.

Similarly it backs up the pilot's impressions and provides measurement of the impact of advanced ATM tools on the cockpit workload, and on the economical impact of such tools.

13 CONCLUSIONS

Several interesting conclusions can be drawn from these trials of integrating a real aircraft within an ATM simulated environment.

Starting with the technical aspects, conclusions can be drawn about the realism of the simulation environment and the performance of the advanced ATM tools investigated.

As mentioned before, these live experiments have proved that the simulation platform exhibits the required level of realism and flexibility to perform this kind of flight trial.

Furthermore, the advanced ATM tools investigated have now reached the required sophistication to handle a real aircraft. Typically they can cope with all the uncertainties attached to the real world and that are often neglected in pure simulation exercises.

Inserting a real aircraft has also the advantage of putting another professional, the pilot, inside the control loop. The large scale real time ATM simulations performed to evaluate/validate new tools with advanced functionality are run with professional controllers but with "pseudo-pilots" flying their computer simulated aircraft via a dedicated interface.

Having a professional pilot in the control loop makes possible to investigate parameters like:

- reaction times in the controller/pilot dialogue
- acceptance, rejection or misunderstanding of clearances
- frequency and type of pilot's initiated requests for aircraft's profile modification.

Advanced ATM tools will change the way in which ATC is performed. It is important that the two major actors in this process, the controller and the pilot, be associated to the validation process from the beginning.

Concerning the subjective aspect of potential workload increase, in the cockpit as well as on the ground, both actors did not experience any significant increase. Neither the pilot nor the controller had the impression of being driven by the machine. The

controller felt at all times completely in the traffic picture.

However, due to the limited number of flights, such a conclusion must be considered with care and will require further investigation.

These trials have also shown that in this kind of exercise, where flight testing is incorporated in real time into an Air Traffic Management environment, it is of prime importance to have the operational people involved from the beginning and correctly trained to use the advanced ATM functionality and the associated HMIs.

Running such kind of exercises can be costly and time consuming because of the infrastructures and the necessary co-ordination involved. However they are the only chance to expose future ATM concepts to an environment as close to reality as possible and to discover potential system limitations that have never shown up in simulation experiments, even in large scale organisational simulations, due to the total control of the operator on the environment. They also give the possibility to have an immediate feedback from all the human actors involved.

Moreover, if they are run a sufficient number of times in a repeatable environment, they can provide the statistical results necessary to assess how a future ATM concept will affect the flows of traffic and the individual aircraft flight profiles, thus giving a solid basis to investigate the associated cost/benefit aspects.

14 REFERENCES

1 *International air traffic handling co-operation* by A. Benoît, Guidance and Control Panel, AGARD Highlights, September 1993.

2 *STANS, an ATC Simulation facility for a Total Air Navigation System* by A. Benoît, C. Garcia Avello and S. Swierstra, EUROCONTROL Report, June 1991.

3 *A report on flight trials to demonstrate the Mode S data link in an ATS environment* by M.C. Cox and S. Swierstra, EUROCONTROL-CAA Mode S Data Link, October 1991.

4 *ODID IV Simulation Report*, EUROCONTROL Experimental Center report No. 269/94, June 1994.

5 *DMA - STANS - ZOC : A compilation of publications*, ATC'91 Exhibition, Maastricht, February 1991

6 *On the development of the BAFR (Basic Aircraft for Flight Research) in Portugal*, L.Campos, J.Azinheira, 17th ICAS, Stockholm, S, 1990.

AGM-130 IMPROVED MODULAR INFRARED SENSOR (IMIRS) FLIGHT TEST

1st Lt Thomas A. Corej
Capt Keith J. Kosan
40th Flight Test Squadron/DOOB
505 W Choctawhatchee Ave Ste 1
Eglin AFB FL 32542-5722
USA

SUMMARY
The AGM-130/Improved Modular Infrared Sensor (IMIRS) weapon system is operationally compatible with the F-15E and F-111F launch platforms. The addition of a rocket motor to the GBU-15, making it an AGM-130, increases the standoff range of the AGM-130.

The IMIRS seeker is an infrared (IR) seeker for the AGM-130, and the AGM-130/IMIRS system provides sufficient resolution for target detection in day or night. Using a two-ship scenario (one weapon-carrying aircraft and one controlling aircraft), the controlling aircraft can stand off at an extended classified range and successfully guide the weapon to impact. The aimpoint update feature of the IMIRS seeker allows for small changes to be made in the aimpoint allowing for precisely attacking a specific point on a target. When the weapon systems officer (WSO) locks-on to a target, he can slew to refine the desired mean point of impact (DMPI) and then lock-on to the new DMPI without breaking the lock on the original aimpoint.

LIST OF SYMBOLS AND ACRONYMS

AFB	Air Force Base
AGL	above ground level
C^3	command, control, and communication
CCF	Centralized Control Facility
DMPI	desired mean point of impact
EMC	electromagnetic compatibility
EMI	electromagnetic interference
FOV	field of view
ft	feet
FTS	flight termination system
GWEF	Guided Weapons Evaluation Facility
IMIRS	Improved Modular Infrared Sensor
IMV	instrumented mock-up vehicle
in.	inches
IR	infrared
IRRTS	infrared resolution target set
KGS	knots groundspeed
km	kilometers
km/h	kilometers per hour
m	meters
mi	miles
MRTD	minimum resolvable temperature differential
NETD	noise equivalent temperature differential
nmi	nautical miles
SAM	surface-to-air missile
TIPS	Thermal Image Processing System
TM	telemetry
TSPI	time-space-position information
USAF	United States Air Force
WDL	weapon datalink
WSO	weapon systems officer

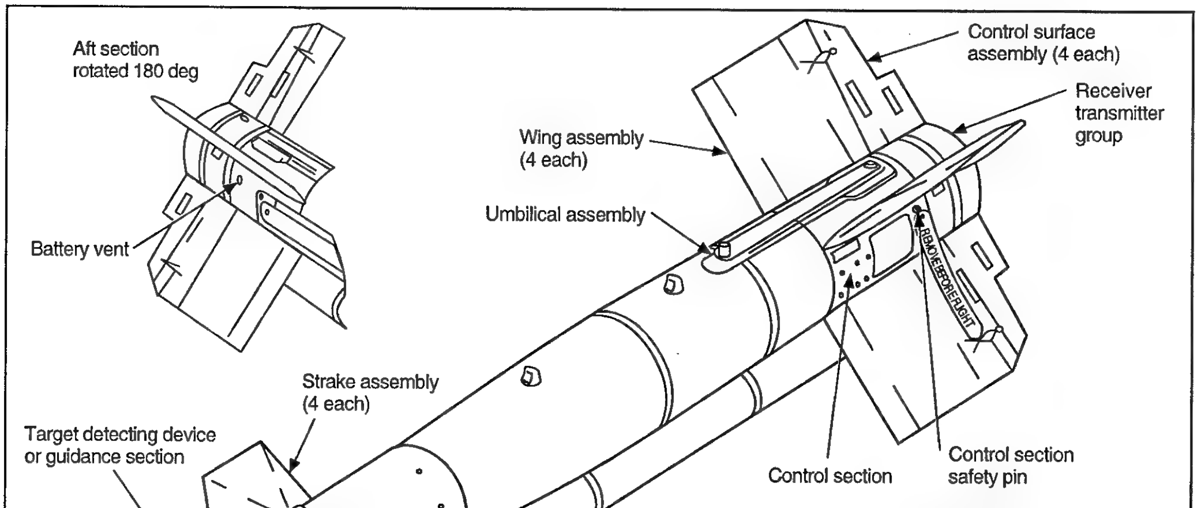
1. INTRODUCTION
This paper describes the methods used to quantify the AGM-130/IMIRS system performance and presents the preliminary results of the production flight test on the F-111F and F-15E aircraft.

Even though today's fighter aircraft have the capability for unparalleled accuracy via direct attack, the high risk that comes with close-in delivery against well-defended targets is often unacceptable. Therefore, today's strategy is to use standoff weapons at the start of a conflict to attack key targets and draw down defenses to a point where the use of direct attack weapons becomes a viable option. In order to increase the standoff range and target detection capability of the F-111F and F-15E, the AGM-130 family of weapons needed a new IR seeker that allowed for target detection from a greater distance and had the advantages of commonality between weapon bodies, better reliability and maintainability, and lower cost. With the better resolution of a new seeker came the opportunity to extend the range of the GBU-15 weapon.

At the request of the USAF Air Combat Command, the 40th Flight Test Squadron of the 46th Test Wing in conjunction with the AGM-130 System Program Office at Eglin AFB, Florida, began conducting flight tests in 1994 to evaluate the AGM-130/IMIRS system compatibility with the F-111F and F-15E.

2. SCOPE AND METHODS OF APPROACH
To meet the requirements for a standoff, precision-guided munition with an improved IR seeker, Rockwell International Corporation developed the AGM-130A/IMIRS system. The AGM-130A (Figure 1) is a modular, precision-guided, air-to-surface munition (MK-84 bomb body) equipped with a rocket motor, wings, and control surfaces to extend the standoff range of this man-in-the-loop system. The guidance section was equipped with the WGU-42/B improved modular IR seeker, which is intended to augment the WGU-33 IR seeker for the AGM-130. IMIRS is an Argon-cooled, midwave IR focal plane array. The system autonomously images the target scene over a span of scene temperatures through passively athermalized optics.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.



Characteristics		
Total weight: (nominal) AGM-130A	3,000 lbs	(119.73 kg)
Length: (nominal) AGM-130A	154.5 in.	(392.43 cm)
Wing span:	59 in.	(149.86 cm)
Strake span:	35 in.	(88.90 cm)
Diameter:		
Motor diameter	9 in.	(22.86 cm)
Target detecting device	15 in.	(38.10 cm)
Warhead	18 in.	(45.72 cm)
Control section	16 in.	(40.64 cm)

Figure 1. AGM-130A

IMIRS provides the WSO with a missile's eye view of the target area on a cockpit display by using the datalink pod on the aircraft to receive video of the target scene transmitted by the weapon. The AGM-130/IMIRS is controlled by the WSO through the same datalink pod on the aircraft used to receive the weapon video. To quantify the performance of this new weapon system, a comprehensive test plan was developed that consisted of the following:

a. function/EMI/EMC tests
b. ground minimum resolvable temperature differential (MRTD) mission
c. operationally representative targets acquisition missions
d. seeker resolution missions
e. maximum range/communication performance mission
f. one live-launch mission
g. countermeasures missions (not covered here).

The ground EMI/EMC and MRTD missions, the in-flight seeker resolution missions, the operationally representative target acquisition missions, and the countermeasures missions were the prerequisites leading up to the live launch mission and successful completion of this test program.

In developing and completing this test, the test engineer drew on the vast EMI/EMC experience of the Air Force SEEK EAGLE Office, the engineering expertise of the personnel at the Guided Weapons Evaluation Facility (GWEF), the extensive and varied land ranges with tactical targets (724 square miles [mi] or 1,875 square kilometers [km]), the vast water ranges (134,000 square mi or 347,000 square km), and the one-of-a-kind instrumented test aircraft all at Eglin AFB, Florida.

3. FUNCTION/EMI/EMC TESTING

3.1 Method

The function and EMI/EMC tests were conducted to verify the AGM-130 with the IMIRS seeker met the compatibility requirements of the safety-of-flight checklist (i.e., the weapon did not interfere with the safety-of-flight systems on the aircraft and the aircraft did not interfere with the operation of the weapon). The compatibility checks were performed on the preproduction and production versions of the AGM-130/IMIRS.

The AGM-130 aircraft system checks were performed both with engines off and with engines running. The aircraft communication, radar, datalink, fuel, navigation, flight control, engine, and video display systems were checked with the weapon operating. The signal environment was monitored by personnel in the frequency control and analysis van.

3.2 Results

No anomalies relating to EMI/EMC were found on any of the aircraft.

4. GROUND MRTD MISSION

4.1 Method

IMIRS Seeker MRTD Measurements. The GWEF, with the assistance of contractor personnel, characterized the MRTD for the AGM-130/IMIRS system in the wide field of view (FOV) through the AXQ-14 datalink pod. This measurement was done both electronically (in the lab) and with a WSO in the aircraft observing the weapon system monitor for minimum resolution of the target patterns. The aircraft engines were not running, but aircraft power to the weapon system, the datalink pod, and the weapon system monitor in the aircraft was utilized for this test. The WSO viewed a target, and the delta temperature was increased until he noted recognition of the four-bar pattern. A smaller target was then put in the FOV and when thermal stability was achieved, the delta temperature was raised again.

IMIRS Noise Equivalent Temperature Differential (NETD) Measurements. The IMIRS was mounted statically in the entrance aperture of a 12-inch (in.) (0.3048-meter [m]) diameter, 60-in. (1.5240-m) focal length off-axis parabola collimator. The seeker, focused at infinity, was aligned to the differential temperature target source at the focal point of the collimator. The seeker's direct video signal was obtained before the datalink from an umbilical breakout connector with the seeker in direct attack mode (not through the datalink). The seeker was connected to test support equipment for power and control of the seeker's modes and settings. This measurement was made at the seeker video output of the sensor.

4.2 Results

The IMIRS seeker was found to have satisfactory MRTD and NETD performance. Actual performance data is classified.

5. TARGET ACQUISITION MISSIONS

5.1 Method

The F-111F and F-15E were flown against tactical (on- and off-range) targets with the AXQ-14 pod. The missions were conducted against on-range targets on the Eglin test range, such as an aircraft shelter, a headquarters building, a simulated surface-to-air missile (SAM) site, and a simulated command and control bunker. One off-range target consisted of a four-lane bridge, nuclear and conventional power plants, and a radio tower. An off-range mission with targets in a snowy background was flown on a low-level route in Nebraska. Targets consisted of bridges, a dam, buildings, and a highway intersection/overpass.

All target acquisition passes simulated a "pickle" of the weapon at approximately 14.5 nautical miles (nmi) (26.9 km) from the target, 420 knots calibrated airspeed (778 kilometers per hour [km/h]), and 1,000 feet (ft) (304.8 m) above ground level (AGL). The WSO called when commencing the run (simulating pickle), and initially the pilot flew straight and level. The WSO searched for the target, giving course corrections to the pilot as required. The WSO called when the target area was detected, when the target was recognized, and when the target aimpoint was identified. The aircraft profile can be found in Figure 2. The WSOs made their calls based on the following criteria:

- *Target detection:* When the WSO could see the target area
- *Target recognition:* When the WSO could distinguish the target building amongst a group of buildings
- *Target identification:* When the WSO could distinguish the DMPI.

5.2 Results

The rating of the targets (from best recognition, identification, and DMPI lock ranges to worst ranges, respectively) is as follows: aircraft shelter; simulated command, control, and communication (C^3) bunker; headquarters building; and the simulated SAM site. The simulated SAM site was probably the most difficult because it was obscured by trees until late in the weapon profile. The aircraft shelter was the easiest to break out because it was a concrete target against a grass and tree background. From the data, it appears that there was no significant difference between the day and night capability of the seeker against these targets with the exception of the aircraft shelter. The recognition, identification, and DMPI lock ranges were consistently and significantly higher for the aircraft shelter with the DMPI lock ranges having the largest disparity on average. For the most part, and ignoring the target lock ranges for the reasons previously mentioned, the recognition, identification, and DMPI lock ranges increased on subsequent runs against the same target.

Tables 1 and 2 show how successful the WSOs were in using the IMIRS seeker. This seeker will allow the aircrew to launch at a larger standoff range with great confidence of being able to locate and hit the target.

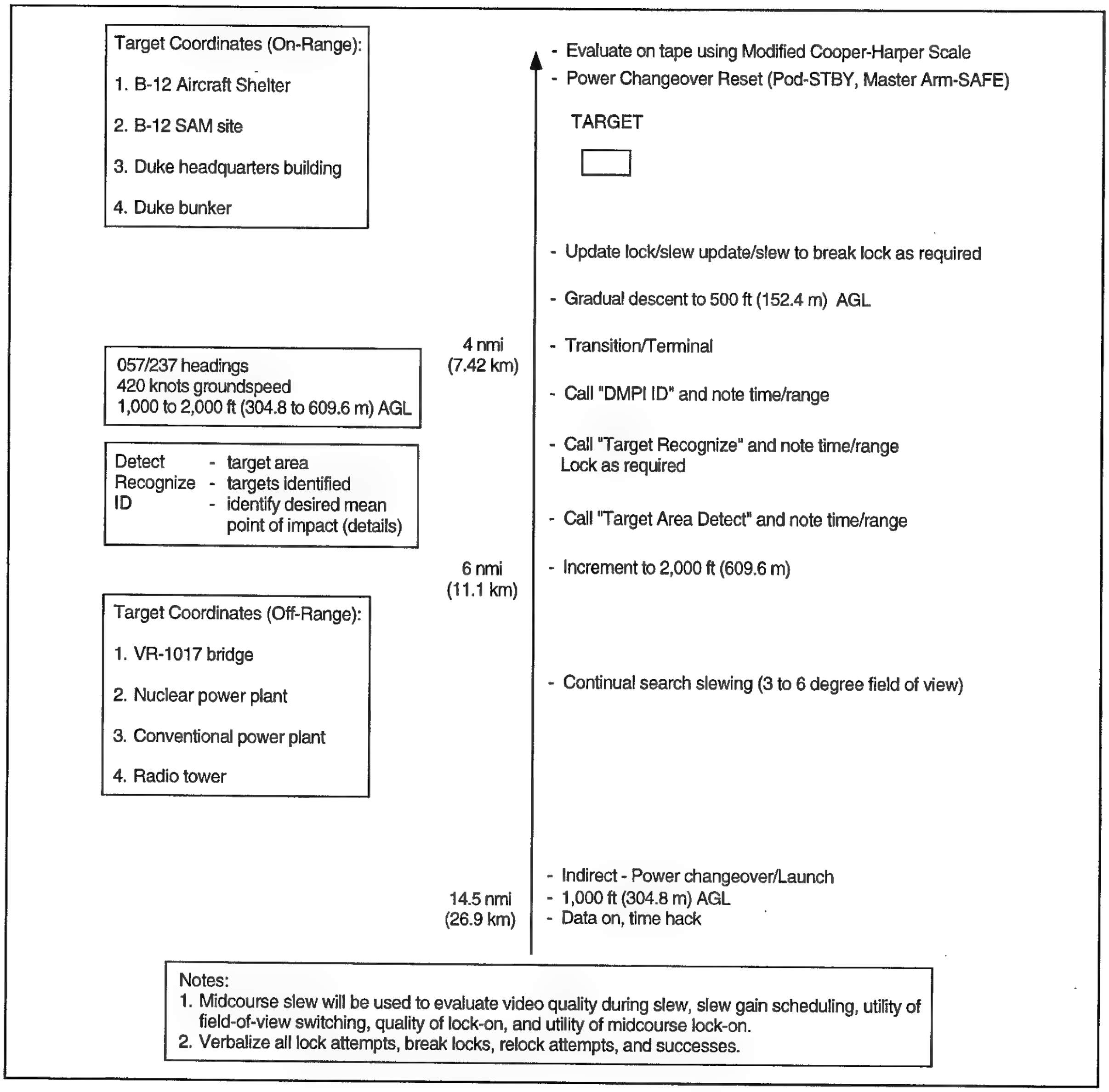


Figure 2. IMIRS On-Range and Off-Range Tactical Target Passes

Table 1. Target Acquisition for Day Missions

Target	Target Recognition	DMPI Identification	Target Lock-on	DMPI Lock-on
Headquarters	24/24	23/24	23/24	22/24
C^3 bunker	19/19	19/19	19/19	15/19
Simulated SAM site	20/20	20/20	20/20	17/20
Aircraft shelter	21/22	21/22	19/22	18/22
Percent	99	98	95	85

Table 2. Target Acquisition for Night Missions

Target	Target Recognition	DMPI Identification	Target Lock-on	DMPI Lock-on
Headquarters	8/9	6/9	4/5	3/5
C^3 bunker	9/9	9/9	7/8	6/8
Simulated SAM site	8/8	8/8	5/6	5/6
Aircraft shelter	10/10	10/10	9/9	9/9
Percent	97	92	89	82

6. RESOLUTION MISSIONS

6.1 Method

The resolution missions were flown to evaluate the spatial and thermal resolution of the IMIRS system. To meet this objective, captive missions were flown against two passive, vertical plywood targets and the active Infrared Resolution Target Set (IRRTS) (shown in Figure 3) on the Eglin range as calibrated engineering standards. The two passive targets consisted of four black painted bars on a white background. The temperature difference between the black and white bars on the passive targets was determined by the paint emissivities, solar loading, wind speed, and wind direction. Each bar on the passive targets was 28 ft (8.5344 m) long and 4 ft (1.2192 m) wide for a 7:1 aspect ratio. One passive target had vertical bars, and the other had horizontal bars. Both the active and passive targets were positioned facing south (180-degree aspect), and they had an 80-degree slope with the ground (10 degrees off the vertical). The passive targets were positioned in a uniform grass background and positioned far enough away from any other objects so that the background in wide FOV was uniform at 2 nmi (3.7 km). The majority of the resolution passes were flown in wide FOV. The active IRRTS board was configured with four vertical hotter bars and three vertical colder bars. Each bar was 2 ft (0.6096 m) wide and 14 ft (4.2672 m) long. A constant temperature difference was maintained as much as possible between the hot and cold bars on the active target. Separate passes were required for resolution tests on each target board.

The missions were flown on the F-15E in the IMIRS/weapon datalink (WDL)/AXQ-14 pod configuration. All resolution passes simulated pickle at 10 to 14.5 nmi (18.5 to 27 km) from the target, 2,000 ft (610 m) AGL, and 420 knots groundspeed (KGS) (778 km/h). The WSO called when commencing the run (simulating pickle), and the pilot flew straight and level at the target. The WSO searched for the target board and gave course corrections to the pilot as required. The WSO called when the target board was acquired (at this point, the individual bars were not resolvable). The WSO called out when he could resolve four distinct black bars. After resolving the bars, the WSO maintained the bar pattern on the target board in the FOV of the seeker.

The WSO was careful not to place the weapon crosshairs on any area of the board. The majority of the captive resolution passes were flown in wide FOV.

Prior to and immediately after each resolution pass, weather data were measured. The weather data included measurements of air temperature, humidity, barometric pressure, wind speed, wind direction, surface visibility, pyranometer, and pyrheliometer (solar loading). These measurements were required to calculate atmospheric attenuation with the LOWTRAN and MODTRAN computer models and to calibrate to target board thermal signatures. The METVAN, parked 700 ft (213 m) southwest of the Thermal Image Processing System (TIPS) van, was used to collect weather data. Ground truth images of the target board being tested were collected by an imaging radiometer operating in the same waveband as that of the IMIRS seeker immediately prior to and after each pass over the target board. Four black-body sources were provided to calibrate the imaging radiometer. The blackbody temperatures were set to near ambient and 10, 30, and 50° Celsius above ambient. The TIPS van, parked 500 ft (152 m) south of the engineering targets, was used to collect the ground truth imagery. The average apparent temperatures for each bar on the targets were calculated from the TIPS imagery and used in later analysis. The Eglin FPS-16 radar system was used to track the target aircraft.

The weather conditions were assessed 2 hours prior to takeoff for the captive resolution tests. The weather minimums for conducting this test were a 5,000-ft (1524-m) cloud deck and 7 nmi (13 km) visibility. Since two of the resolution targets were passive, they used sunlight to heat up the different color paints enough to get a sufficient temperature differential.

6.2 Results

It was found that black hot was better for target detection, but white hot was better for identifying four distinct bars. In almost all cases, the bars on Target 3 (passive, horizontal bars) were the first to break out for identification. The active IRRTS board heated the colder bars to approximately 2° Celsius above ambient to provide more control over the colder bars.

Weapon video from the resolution tests were analyzed to determine the time at which the WSO identified the four hot bars on the engineering targets. Also, three analysts reviewed the same imagery to determine the time at which they could identify the four hot bars when viewing the tape on a video monitor in a laboratory environment. The target identification times were used to calculate the target identification ranges from the time-tagged target range time-space-position information (TSPI) data.

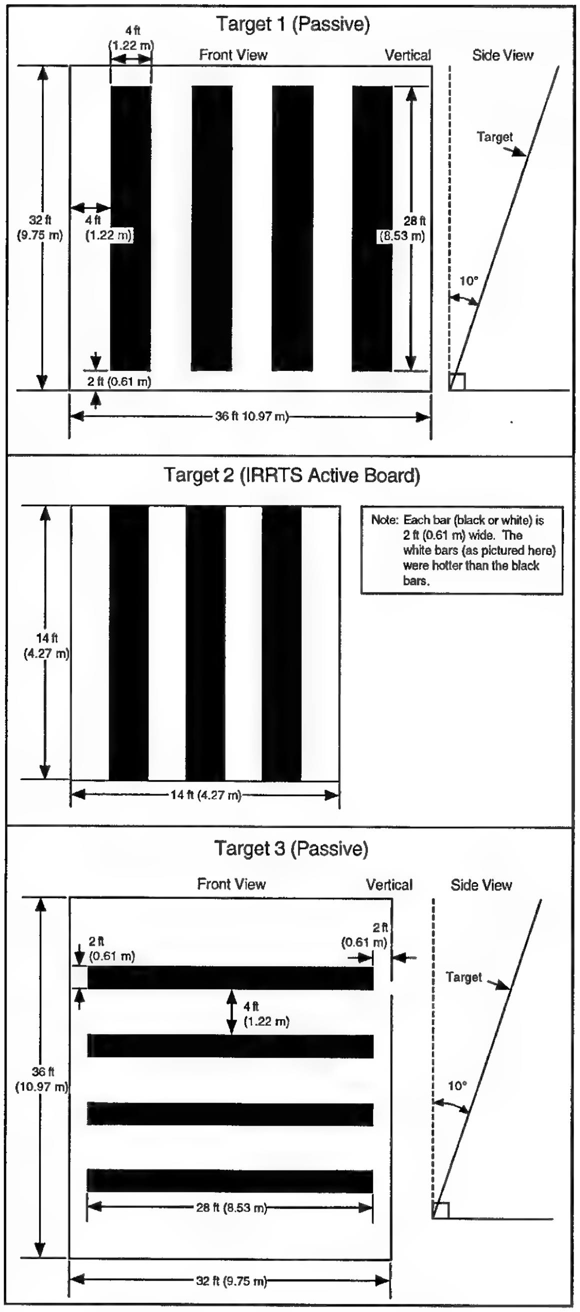


Figure 3. IMIRS Resolution

The 14 passes against the passive targets flown in wide FOV and white hot were analyzed to determine if a relationship existed between target identification range and the target bar temperature differentials (delta T) measured by the TIPS imaging radiometer. A plot of range versus delta T shows that no strong relationship exists between increased delta T and increased identification range. Therefore, range performance was limited by the spatial resolution of the seeker significantly more than it was limited by the target contrast. Consequently, the thermal resolution of the IMIRS seeker was not reached during the captive-carry resolution tests. However, the IMIRS thermal resolution was tested during the MRTD tests conducted with the seeker operating in a hangar.

7. MAXIMUM RANGE/COMMUNICATION PERFORMANCE MISSION

7.1 Method

This portion of the test was flown to assess the communications performance of the system by looking at multipath, signal-to-noise ratio, datalink, and range effects. This mission had an F-111F carrying an instrumented mock-up vehicle (IMV)/ IMIRS/WDL, and an F-15E configured with an AXQ-14 pod. These test missions were performed following two-ship standoff attack profiles with the F-111F serving as the delivery or truck aircraft and the F-15E serving as the standoff controller aircraft on each pass. The F-15E flew in the same heading as the F-111F in a loose-line abreast formation approximately 1/2 nmi (0.926 km) apart at range.

The F-111F simulated an attack of a land target (the simulated headquarters building on Test Area B-12) while the F-15E stood off over the Gulf of Mexico. The target was a large building that was two stories high (with a small cupola on top of it). The F-111F simulated a launch at approximately 14.5 nmi (27 km) from the target while at 1,000 to 2,000 ft (305 to 610 m) at 450 KGS (834 km/h). The F-111F would simulate the weapon going Transition/Terminal at approximately 4 nmi (7.4 km) from the target with a gradual descent to 300 ft (91 m) AGL.

The F-15E stood off at approximately 25,000 to 31,000 ft (7,620 to 9,449 m) AGL and initially at a base distance from the F-111F. The separation distance between the F-111F and the F-15E was controlled from the Centralized Control Facility (CCF). The F-15E received the video signals from the F-111F and acted as the controlling aircraft on each pass. After the F-15E acted as the weapon controller at each distance, the separation between the F-111F and F-15E was increased and another set of passes was accomplished.

This process was repeated until the test engineer terminated the test when it was determined that the maximum required separation range was reached. The weather minimums set for this test were a 2,500-ft (762 m) cloud ceiling and 3 nmi (5.56 km) visibility.

7.2 Results

The seeker was operated in the EDGE/BLACK mode for runs 1 to 4 and EXP/WHITE for runs 5 to 9. After pass 4B, both aircraft switched to using EXP/WHITE to get a better video scene consistent with the target heating up during the mid-morning hours. Wide FOV was primarily utilized on all runs. The F-15E acted as the control aircraft one time at the first two distances. The F-15E acted as the control aircraft two times at the remaining three distances.

AXQ-14 Pod Results. During the initial runs, no real problems were noted; however, as the distance between the weapon and pod was increased, there were more frequent command link dropouts. On one run, the conditions may have been significant enough that accurate weapon delivery may not have been possible. Similar multipath related video fades were experienced at extended separation ranges. On two runs, the laser fire button did not command Terminal as expected after Transition was selected. This may have been caused by the extreme ranges at which the aircrew was operating.

Actual separation distances, recognition and identification ranges, and additional comments are classified.

8. LIVE-LAUNCH MISSION

8.1 Method

After the satisfactory dress rehearsal missions, one live-launch mission was performed. A target designation/identification pass, IMV passes, and three other types of passes (alpha, bravo, and charlie) were executed against the launch target. On the downwind leg of one pass, various weapon functions were checked with telemetry (TM). On the alpha pass, radio confirmation was made between the aircrew and the test engineer in the CCF, and the aircrews practiced the timing and aircraft spacing. On the bravo pass, a power changeover was accomplished (the weapon used power from the weapon batteries, not from the aircraft), and a practice pass over the target was performed. The target was a 32- by 40-ft (9.75- by 12.2-m) painted billboard type target with alternating black and white squares that decrease in size. (See Figure 4 for a diagram of the launch target.) The safety engineer conducted a TM check of the flight termination system (FTS) destruct signal and directed the range controller to ensure no personnel were within the weapon flight profile. The radar TSPI trackers and cinetheodolites performed system checks on the alpha and bravo passes and recorded data on the charlie pass, which was the weapon release pass. The aircraft controller in the CCF adjusted the standoff range based on winds and vectored the aircraft into the run-in heading. The aircrew launched the weapon and performed an egress maneuver by turning right. The high-speed cameras began filming when the weapon was approximately 200 ft (61 m) from the target. The WSO selected Transition, Terminal and locked-on to the target for automatic track.

The live-launch was performed using single-ship tactics. In single-ship tactics, the aircraft carrying the weapon performed an egress maneuver to the right from the run-in heading after releasing the weapon.

Planned AGM-130A/IMIRS launch conditions were as follows:

Airspeed - 480 knots true airspeed (890 km/h)
Altitude - 2,000 ft (610 m) AGL
Launch range - 13.5 nmi (25 km)
Cruise altitude - 2,000 ft (610 m) AGL

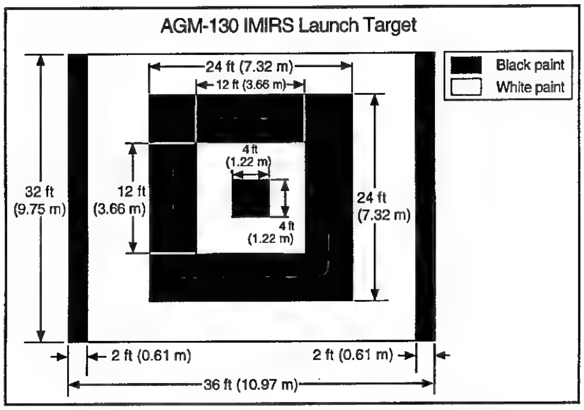


Figure 4. AGM-130 IMIRS Launch Target

If the weapon failed to respond to datalink commands after launch, a "dead-eye" radio call was to be made. If command link could not be re-established, the safety engineer planned to utilize the FTS by making a "destruct, destruct, destruct" radio call when the weapon was clear of the manned test sites. The chase aircraft was to immediately egress the area and then call "chase clear" before the destruct command was sent.

A safety footprint was established in case of a ballistic failure (control surfaces malfunctioned and vectored the weapon into the ground immediately after launch) and no motor ignition. In the event of no rocket motor ignition, a crew was available at Test Area B-70 to find the remains of the weapon after ground impact and to safe or detonate the weapon fuze in the event it did not function. After a successful target impact, Explosive Ordnance Disposal crews verified fuze function and declared the remains of the weapon safe from any further explosive detonations.

A postmission debriefing was conducted after the live launch. The WSO debriefed the test team with the videotape recording, and a preliminary assessment of the success of the target impact was made.

8.2 Results

The aircraft controller in the CCF adjusted the standoff range based on a tail wind and vectored the aircraft into the run-in heading. The run-in heading was chosen to be 235 degrees—2 degrees off the centerline of Test Area B-70. The aircrew launched the weapon and performed an egress maneuver by turning right (335-degree heading). The high-speed cameras began filming when the weapon was approximately 200 ft (61 m) from the target. The WSO selected Transition, Terminal and locked-on to the target for automatic track.

The WSO locked the seeker onto the DMPI and performed several aimpoint updates as he got closer to the target. Otherwise, the WSO remained hands-off to allow the seeker to track the target automatically. Using this method, the weapon

was able to successful track the target automatically. This mission was the culmination of all previous IMIRS ground and captive-carry missions.

6. REFERENCES AND ACKOWLEDGMENTS

For reference materials and acknowledgments, please contact your AGARD liaison.

Ensuring the GNSS Onboard Integrity Function Under Adverse Conditions: Feasibility and Flight Test Results

Carsten Butzmühlen
Institute of Flight Guidance
Technical University Braunschweig
Hans-Sommer-Str. 66, 38 106 Braunschweig
Germany
Tel: xx49 531 391 3709
Fax: xx49 531 391 5954
E-Mail: c.butzmuehlen@tu-bs.de

1 Abstract

With an increasing system and technology performance of satellite navigation components, the Global Navigation Satellite Systems (GNSS) conquer more and more fields of military and civil applications. Due to the undisputed high level of accuracy and its marginal needs of terrestrial infrastructure, satellite navigation is in principle the most suitable candidate for positioning tasks under adverse environments where conventional radio navigation aids fail. Considering this background, the Institute of Flight Guidance and Control participated recently in a flight test program in Lugano, Switzerland supported by the Swiss Federal Office of Aviation (FOCA).

Flight tests were performed under highly dynamic and adverse conditions with the additional use of low-cost inertial information. The landscape in which these test were realized leads to the risk of extensive shadowing of the space vehicles, thus increasing the probability that the GNSS is not available in order to compute a position solution. Additionally, the mountains provide a reflecting surface of the radiofrequency signals. Hence, the possibility of multipath reception is given here as well.

This paper deals with the current means that are used to achieve the accuracy and the integrity that is necessary for high-precision and safety-critical procedures. The methods are discussed briefly and flight test results are presented.

2 Introduction

Satellite navigation systems are very accurate means of determining the user position with passive and comparatively inexpensive user equipment. Since the American satellite navigation system GPS has been declared fully operational, the service of a navigation system is available, which is more accurate than any other medium- or long-range navigation system.

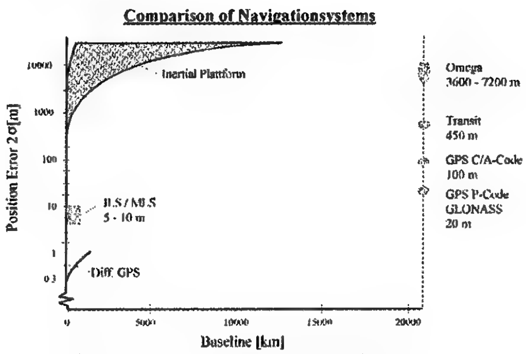


Figure 1: Comparison of different Navigation Systems

As figure 1 shows, satellite navigation systems have the potential to become the most versatile navigation system for short- and long-range navigation applications. In order to fully utilize this potential, a number of factors have to be taken into account which influence the accuracy and the integrity of this system.

3 Satellite Navigation

3.1 Measurement

The position determination with satellite navigation systems is performed by using the 'propagation time measurements' of electromagnetic waves which originate from satellites in specified orbits. These measurements are converted into distances using the speed of light as the known speed of propagation. Basically three types of measurement variables are available : the code-pseudorange, the carrier phase and the doppler-frequency (a derivative of the carrier phase).

The figure 2 illustrates the basic principle of the user position calculation using three measurements. Since the time-scale of the user receiver can not be synchronized with the time scale of the satellites without the help of a high-precision atomic clock, four satellite measurements instead of three are necessary to calculate the 4D user solution (3D position and time).

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

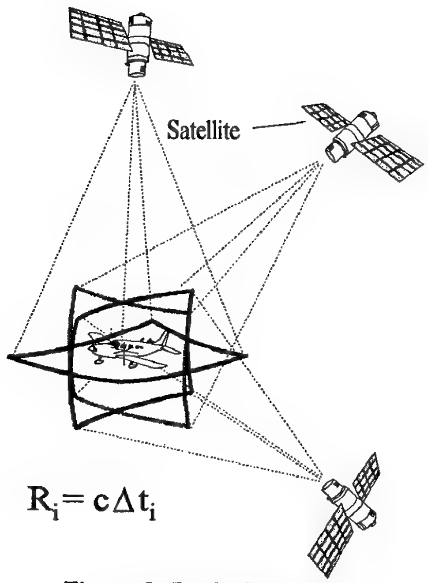


Figure 2: Basic Principle of Position Determination

3.2 Accuracy

To achieve a certain level of accuracy, ground-based differential augmentation systems are needed for the satellite navigation system. These subsystems monitor the navigation signal and broadcast appropriate range corrections to the user by the means of a dedicated data channel (see figure 3).

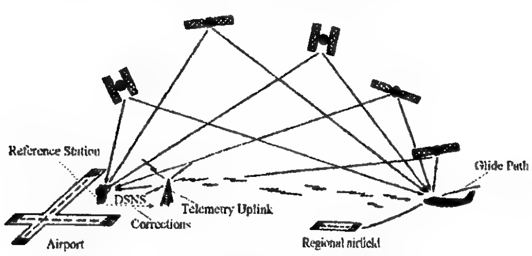


Figure 3: Ground-based Differential Augmentation Systems

Another method to enhance the resolution of the code-base navigation solution is known as carrier-smoothing. Furthermore the carrier-phase relationship between the received and the internally generated signal can be measured and used to increase the position accuracy of the satellite navigation systems

3.3 Integrity

In the context of navigation, the integrity is defined as the 'ability of the navigation system to provide the user with navigation signals that are within specifications or with a notification that the user should not use certain navigation signals' [2]. Thus, the integrity monitoring of the satellite navigation systems is concerned with the quality control of the radionavigation signals. One possible approach is to externally transmit information about the state of the system to the user by means of a dedicated data channel. The other possible approach to integrity monitoring is to perform the monitoring onboard the aircraft.

Since the ground integrity monitoring is not able to detect errors that arise in the vicinity of the user, the onboard integrity monitoring is of essential importance to the satellite navigation system.

3.4 Failure Modes

The errors incurred on the measurements of the satellite navigation system can be divided into three areas. Errors due to the space segment are satellite clock errors and satellite position errors. Further errors occur while the signal travels from the satellite to the receiver (propagation errors). The receiver-antenna combination is the last source of errors (multipath, loss of line-of-sight due to shadowing, interference and jamming).

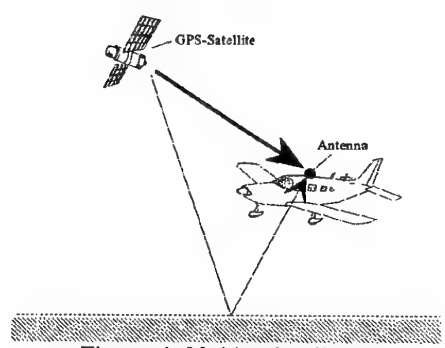


Figure 4: Multipath effects

Unresolved issues are the influence of multipath effects on the achievable position accuracy, in particular in the vicinity of reflecting surfaces (see figure 4), the interference and the deliberate jamming of radiofrequency signals.

4 Integrated Navigation Systems

The basic concept of an integrated satellite-/inertial-navigation system is illustrated in figure 5. The overall accuracy performance of such a system is determined by the satellite subsystem. Sensor errors of both the satellite- and the inertial-subsystem are estimated on-line.

The inertial sensors are an ideal complement to GNSS due to their good dynamic properties, although they can be characterized by a long-term drift as a result of misalignment and gyro errors. Since the inertial-subsystem can be calibrated by the satellite-subsystem and as

long as the inertial error properties can be sufficiently modeled, the integrated system can keep the overall position accuracy even during outages of the satellite navigation system.

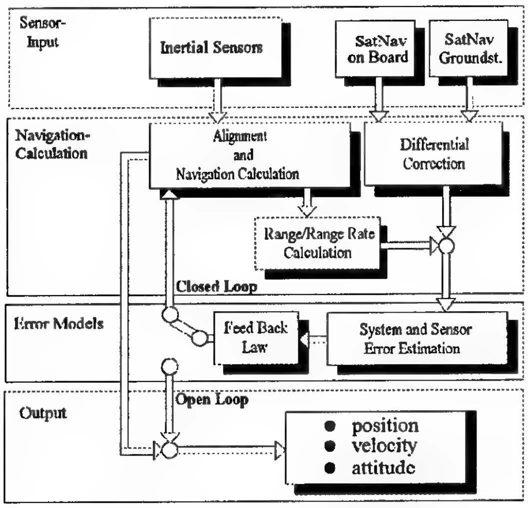


Figure 5: Concept of an Integrated Navigation System

5 Accuracy Aspects of GPS

5.1 Differential GPS

The differential GPS technique is based on a comparison between a precisely determined stationary reference position and a GPS standalone navigation solution for the user position. In this comparison, the errors of the satellite clock, the satellite position and the effects of the atmospheric errors can be determined. Transmitting these error correction information to the user, it is possible to compensate for all the above mentioned errors.

For approach and landing procedures, where there exists a direct line-of-sight between the reference station and the user aircraft, a Local Area DGPS with a customized ultra-high frequency data link can be used. However, for low-level flight tests in valleys and in mountainous areas, this technique is not adequate because the availability of the telemetry UHF data link is reduced due to terrain formations. In these situations, the correction DGPS-signal has been provided via a low-frequency transmitter that has been established by the Institute of Applied Geodesy (IfAG, Germany). The low-frequency data are broadcasted in a format recommended by the Radio Technical Commission for Maritime Services (RTCM).

A parameter affecting the achievable accuracy while applying the differential corrections to the user standalone GPS navigation process is the baseline length, i.e. the distance between the transmitter of the reference station and the user aircraft.

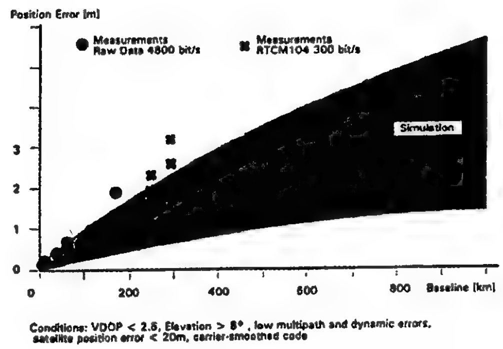


Figure 6: Accuracy of Differential GPS

However, using the low-frequency data link, another parameter becomes important. Since the transmission rate of the differential corrections is significantly lower, the age of the correction data has an influence on the achievable accuracy. This is shown in figure 6, where the accuracy that has been achieved with Local Area Differential GPS and with Wide-Area Differential GPS using the RTCM data format is shown.

5.2 Carrier-Phase Solutions

With standard algorithms for DGPS processing like carrier-phase smoothed code measurements, it is possible to achieve an accuracy in the m-range. However, with the application of GPS phase ambiguity resolution techniques, the achievable accuracy can be increased down to a cm-level. With this level of accuracy, it is possible to use the satellite navigation system as a reference system for flight inspection purposes.

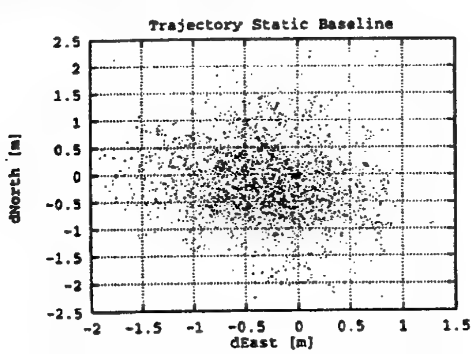


Figure 7: Carrier Phase Position Solution

Figure 7 illustrates the potential of the carrier phase navigation solution in a static test environment. The figures 8 and 9 show the

standard deviation of the carrier phase solution for the latitude, longitude and altitude, respectively in a flight test.

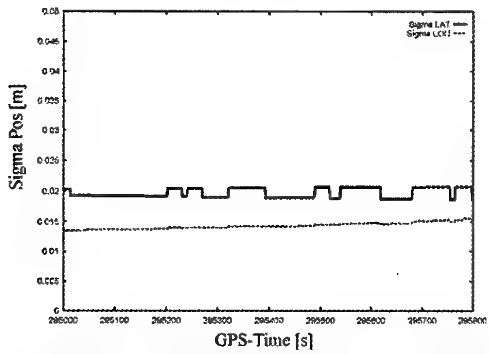


Figure 8: Standard Deviation of Position Solution with Carrier Phase (Latitude and Longitude)

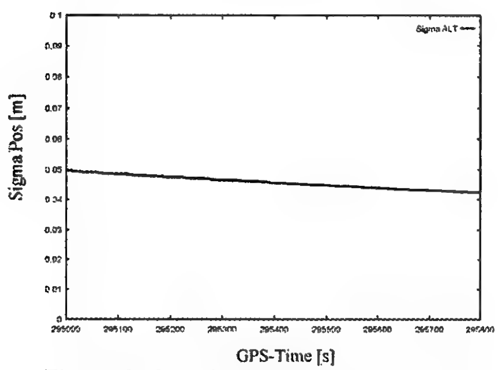


Figure 9: Standard Deviation of Position Solution with Carrier Phase (Altitude)

Since the accuracy of the carrier phase solution approaches the cm-level, the technique of using carrier phase information of satellite navigation systems can be used as a reference system during flight inspection procedures.

Some of the current algorithms for the resolution of the integer ambiguities use static techniques for the initial determination of the ambiguities, and furthermore, rely on continuous satellite tracking during the flight. Yet, it is not feasible for an aircraft to stand on a taxiway and wait, until the search space has been narrowed down to a sufficient level to solve for the ambiguities. Additionally, no continuous tracking of all received satellites can be guaranteed, since the flight path is provided by the ground controllers with aspects of air traffic flow.

Thus, the satellite navigation carrier phase techniques must be able to resolve the ambiguities 'on-the-fly' during the flight. It is very important that these integer ambiguities are solved correctly, since wrong combinations would cause position errors which are sufficiently large to violate the accuracy requirements for precision landings.

In many ambiguity resolution techniques, the pseudorange-residuals of a solution are used as a measure of the quality of the solution. However, in order to generate residuals, a redundancy of at least one satellite is necessary. Thus, a minimum of at least five satellites is needed for the ambiguity resolution techniques.

In mountainous areas such as the Lugano airport, the visibility is obviously limited to an even greater degree than with most other situations. A rigorous preplanning of the measurement times and a placement of the reference station for optimal satellite visibility becomes an issue of even more importance than it is with the differential techniques.

5.3 Integrated Navigation System

In the integrated navigation system an optimal estimator is used as an observer of the navigation process. In the observer, the appropriate error states of both the inertial navigation process and the satellite navigation process are used to estimate the system- and the sensor-errors of the integrated navigation system. The different error-models of the sensors are weighted accordingly to the user dynamic.

Through the use of appropriate error models, the navigation solution (position and velocity) is robust and a high degree of accuracy is achieved. Even with the total short-term loss of the satellite navigation, the achievable level of accuracy using the integrated navigation system is only slightly decreased. This is shown in figure 10, where for a period of 120 seconds, all satellites are masked. If an appropriate error modeling of the errors of the inertial sensors is performed, even 'low-cost' inertial sensors can be used in combination with the satellite navigation system.

6 Lugano Flight Tests

The performance of different onboard integrity monitoring approaches is evaluated using data of the flight test program that has been carried out in Lugano, Switzerland. The Lugano-Agno airport is situated within an extremely mountainous region on the southern side of the Alps. The airport has one concrete runway (RWY 03/21), running approximately north-south with a length of 1350 meters. It is surrounded by mountains as tall as 4000 m. The figure 11 demonstrates the view from an aircraft approaching from the north.

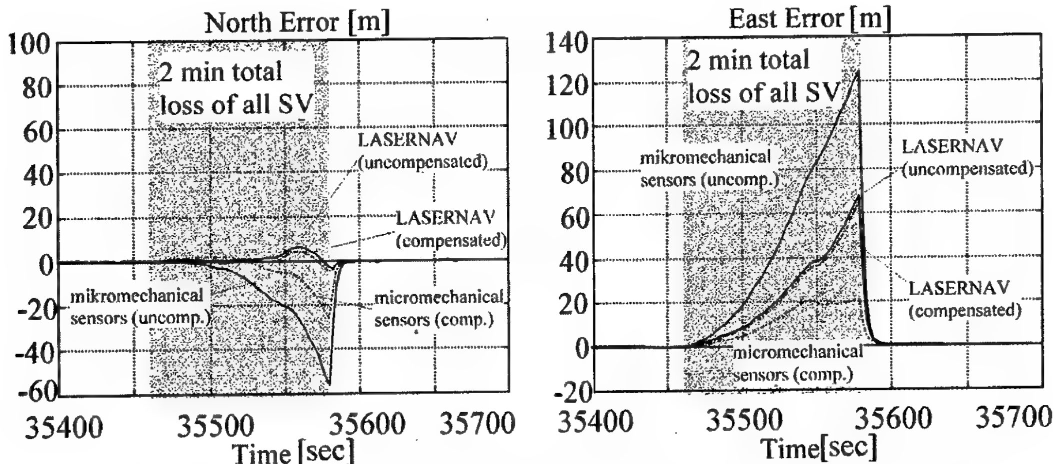


Figure 10: Loss of position precision due to total masking of satellite navigation

Due to mountainous terrain to the north of the airport, the approaches currently take place from the south. A DGPS approach procedure was developed that would save about 10 minutes flight time for aircraft approaching from the north. In the figure 12 the DGPS approach procedure is displayed.

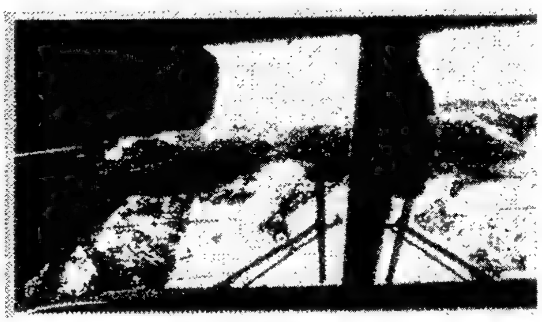


Figure 11: View from an aircraft approaching Lugano-Agno from the north

6.1 Accuracy

6.1.1 Flight Tests

To get an advance estimate of terrain blocking for the ground station, data from a terrain model had been evaluated for a position on the airport runway by the Technical University of Zurich (ETH). This elevation-azimuth blockage diagram is shown in figure 13 overlayed with actual tracking data from a static test.

Each of the vertical lines shows ascent or descent of a satellite. Overlaps with the terrain contour indicate visibility below the model value, blank areas (visible especially between 30 degress and 90 degrees and at 300 degrees of azimuth) indicate hills not included in the model due to model resolution limitations. The high elevation mask that can be experienced at the location of the reference station due to the mountainous landscape is quite obvious.

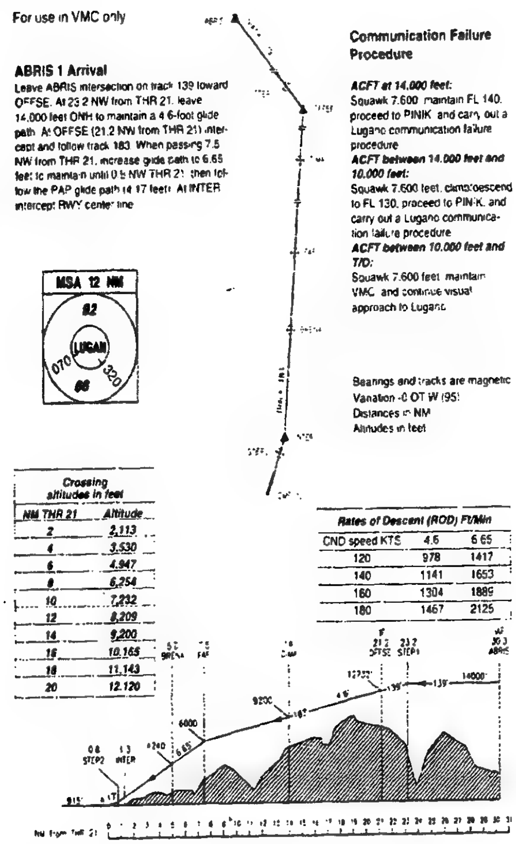


Figure 12: DGPS Approach Procedure

The figure 14 illustrates the ground track of the flight test that was used in the evaluation of the achievable accuracy.

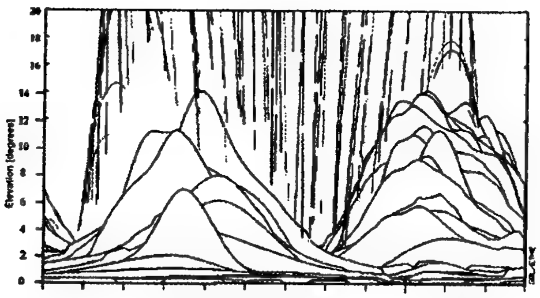


Figure 13 Elevation Mask at the reference station

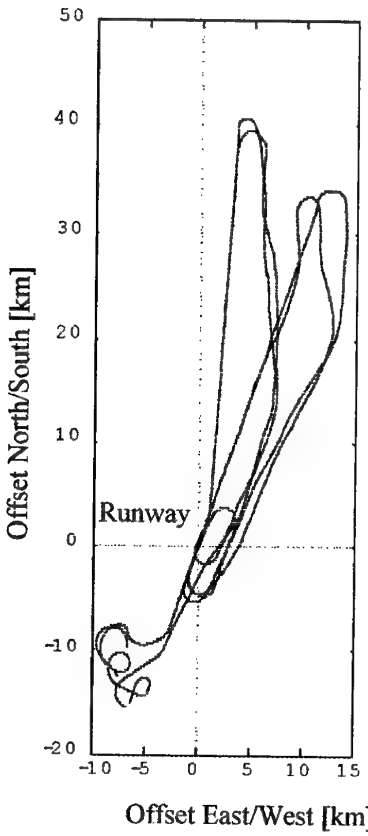


Figure 14: Ground Track of Flight Path

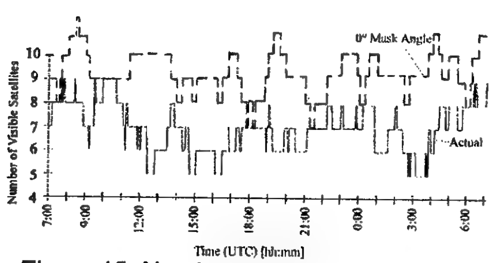


Figure 15: Number of received Satellites

To investigate the quality of the chosen position and reception of the satellite signals a 24h static test was performed. Figure 15 shows the number of satellites received in contrast to the satellites available without terrain masking. As expected, the mountains reduce the number of visible satellites significantly, down to five during several periods of the day.

6.1.2 Accuracy Results

For the one-week trials a GPS-reference station and a laser tracker were set up in the vicinity of the southern runway threshold and surveyed using known geodetic reference points. Two different GPS receivers were used, one of the guidance task at hand, the other as a reference to detect receiver specific errors. As reference systems, both laser tracker and an on-the-fly ambiguity resolution algorithm using pure GPS carrier phase measurements have been used.

As Figure 16a shows, approaches from the north were flown directly and with an offset, starting at FL140. Approaches from the south were planned, too, but interference problems of the GPS signals due to external transmitters in the area shown in the figure forced cancellation of this part of the tests. Figure 16b details the parts of the flight path where telemetry reception was stable, the range of more than 30 km at approach allowed a stable GPS/DGPS-transition.

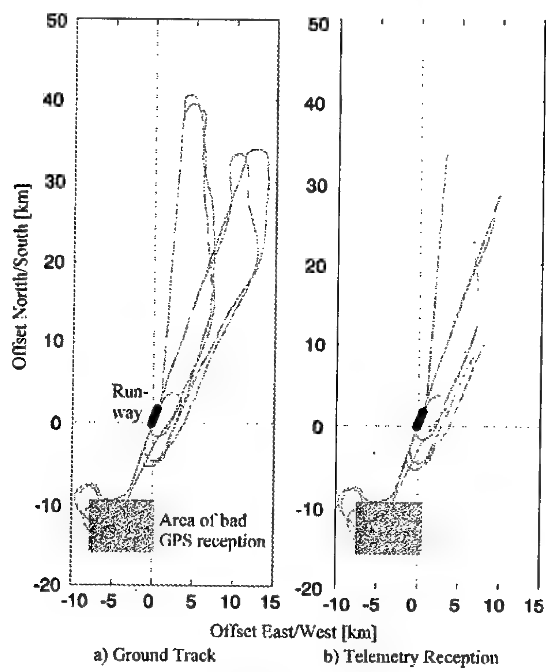


Figure 16: Flight Path with Area of bad GPS reception

As can be seen from figure 16, as well, interference caused loss of GPS L1 signal reception in a relatively large area south of the airport. Approaches from the south could therefore not be performed using GPS-based techniques. In this situation, the source of the

ground-based interference was determined to be constant for all the approaches. But often the interference source might as well be intermittent.
The achieved position accuracy was good (see figure 17), although the lower number of satellites due to the loss of the line-of-sight of low-altitude satellites to the east and to the west of the flown approach increased the error level. At a distance of 1.5 nautical miles from the runway threshold, a shadowing of one satellite by the aircraft caused a deviation in the along-track error.

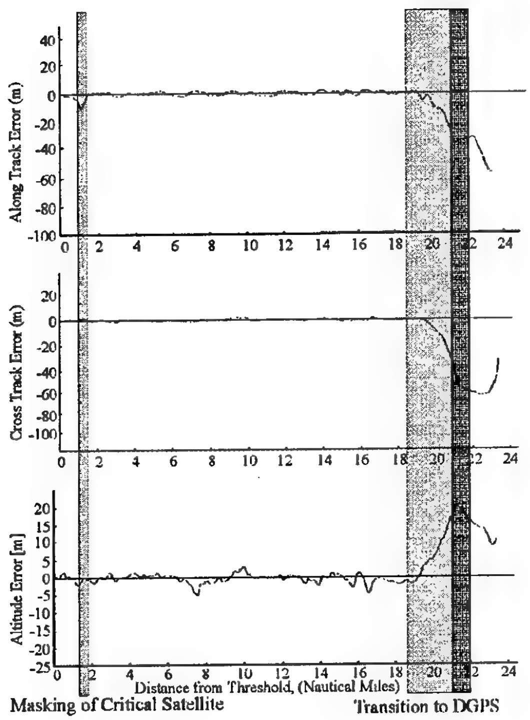


Figure 17: Accuracy during a typical approach

The number of satellites visible from the user station decreases as the aircraft descends toward the threshold. In this case, due to the positioning of the reference station, the number of satellites used for positioning after the transition to DGPS depends mainly on the number of corrections from the ground. Therefore the measurement redundancy needed to allow aircraft maneuvers with subsequent shadowing of further satellites is limited.

6.2 Integrity

6.2.1 Flight Tests

Since the integrity monitoring algorithms are evaluated using simulated errors that are introduced into the measurements, a part of the flight path has to be chosen that contains at least six received satellites (i.e. the minimum requirement for RAIM).

The figure 18 illustrates the horizontal flight path and in figure 19 the height above ground of the particular flight test that is used for the evaluation of the integrity monitoring is displayed.

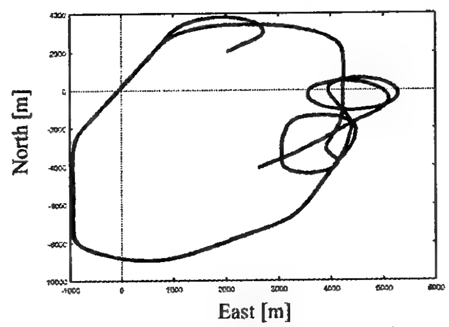


Figure 18 Horizontal Flight Path

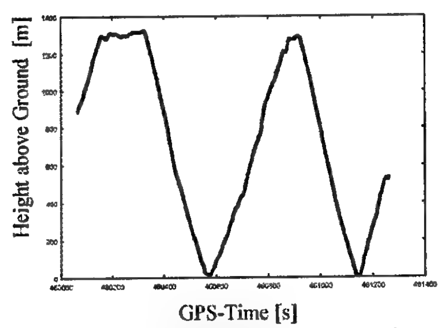


Figure 19 Height above Ground

The figure 20 displays the number of received satellites during that particular flight test. There is only a short time interval, in which six or more satellites are received. Only during this very short period, RAIM can be performed. Only a very small part of the flight test program is usable.

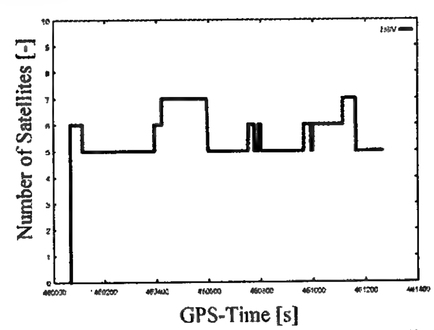


Figure 20: Number of Received Satellites

The errors that have been simulated onto the measured pseudoranges are selected according to the satellite constellation that is depicted in figure 21. The table 1 contains the parameters for the three simulations.

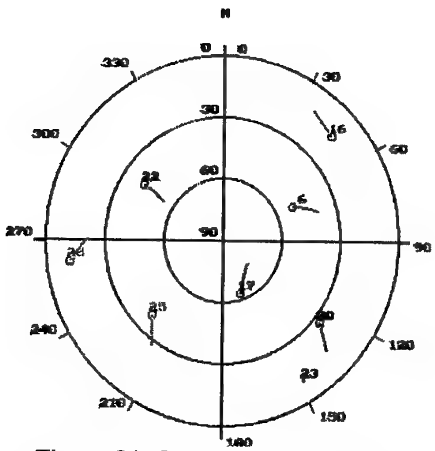


Figure 21: Satellite Constellation

Simulation 1		
Time [s]	SV	Error
460400.0 - 460450.0	22	ramp
460430.0 - 460450.0	25	ramp
Simulation 2		
460400.0 - 460450.0	6	ramp
460430.0 - 460450.0	16	ramp
Simulation 3		
460400.0 - 460450.0	7	ramp
460430.0 - 460450.0	20	ramp

Table 1: Error Simulations

6.2.2 RAIM Performance

The performance of RAIM has been evaluated using 2 approaches ([4],[9]). The detection and following identification of a faulty satellite is used as an observation of the integrity control algorithm, yet this observation is not used to exclude the identified satellite from the navigation solution. The pseudorange residuals are of prime interest for the RAIM algorithms. Yet, due to the way these residuals are calculated, the residuals are correlated among all channels that are used for GNSS navigation. The figure 22 illustrates this effect. Furthermore, the effect of the constellation change on the development of the pseudorange-residuals is noteworthy. A correct assignment of the error that are modeled onto the pseudoranges is not possible with this phenomenon.

Common to all the RAIM algorithms is the limitation that only one error source is detectable and can be identified. This leads to a situation (GPS-Time 460430), where the modeled errors cancel themselves out.

The figure 23 displays this limitation of all RAIM algorithms. A situation is identified where no error source is detected. The whole constellation is declared usable and no satellite must be excluded, yet errors of considerable amounts are introduced on two satellites.

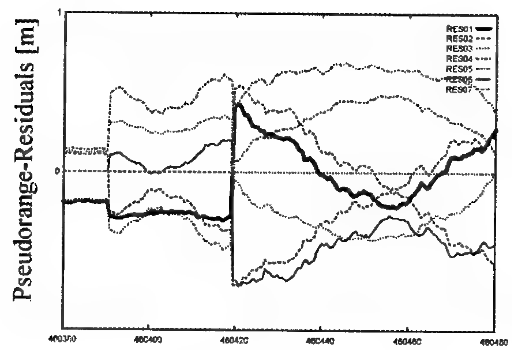


Figure 22: RAIM-Residuals

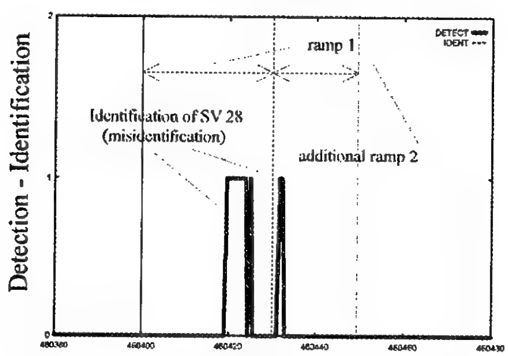


Figure 23: Identification Properties of RAIM

6.2.3 AAIM Performance

The other possible approach to onboard integrity monitoring of the satellite navigation systems is the use of information available from other, independent sensors onboard the aircraft. The performance of the AAIM algorithm is evaluated using the same satellite constellation and the same error-scenarios that have been used for the RAIM algorithms.

Since the implemented algorithm uses differentially corrected GNSS pseudorange measurements, the clock offset of the GNSS user receiver is still included in the residuals that are used for integrity monitoring purposes. However, the residuals used here show no correlation between each channel (apart from the clock offset distribution). Thus, the erroneous pseudorange can easily be detected by simply inspecting the development of the residuals. Again, since there is no correlation between the channels of the GNSS receiver due to the process of the navigation solution, the residuals are different for each error-scenario investigated. This is shown in figures

24 and 25, where the residuals for the error simulation 1 and 2, respectively, are displayed.

Once the second introduced error ramp reaches a size that has to be detected, the identification of both the error sources is the correctly performed. This is shown in the figure 26 for the error simulation 1

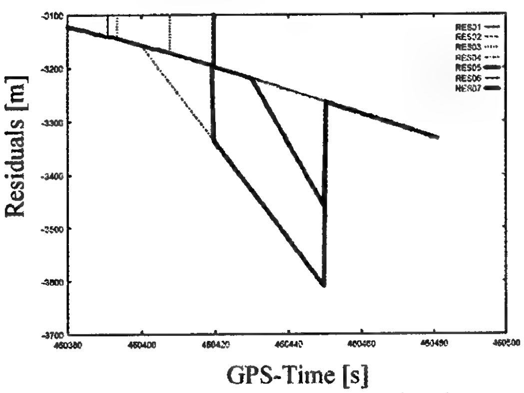


Figure 24: AAIM-Residuals, Simulation 1

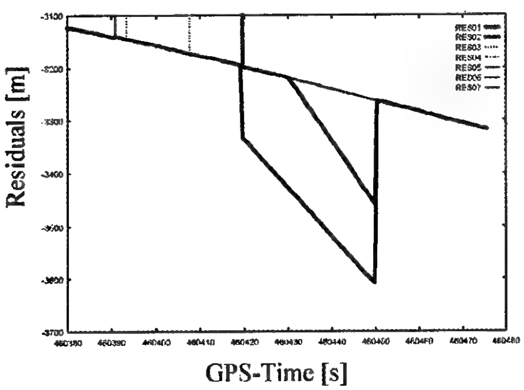


Figure 25: AAIM-Residuals, Simulation 2

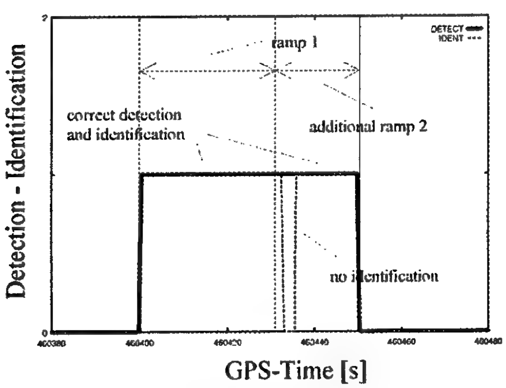


Figure 26: AAIM Identification Properties, Simulation 1

6.2.4 AAIM versus RAIM

The RAIM algorithms present extreme disadvantages and are, in general, not able to cope with multi-error scenarios. The identification scheme used for both algorithms shows tremendous insufficiencies, Additionally, the identification process is strongly influenced by the satellite constellation and its geometry.

Using the AAIM-algorithm, it is possible to identify erroneous satellites even in multi-error scenarios. The identification of the faulty satellites occurs earlier (i.e. with a smaller error introduced into the pseudoranges) and the identification properties do not depend that much on the satellite constellation and its geometry.

7 Conclusion

In order to comply with the accuracy as well as the safety requirements for safety-critical application, a continuous monitoring of the system status in its dynamic environment is essentially needed, in particular with GNSS.

Interference of local sources with satellite navigation signals has been detected and severely limits southern approaches to Lugano using satellite navigation systems. The average number of visible satellites is lower, this limits the amount of maneuvering allowable for the aircraft. In order to extend the limitations on satellite visibility it might be desirable to place the reference station in a less obstructed area.

The accuracy and integrity of integrated navigation systems seems adequate, but limited satellite visibility and telemetry loss must be taken into account in system design to assure continuous operation. Yet, pure satellite navigation solutions will not ensure sufficient integrity and accuracy. The combination of GNSS with self-supporting inertial information presents itself as an adequate solution.

8 References

[1] - : ICAO ANNEX 10' Aeronautical Telecom-munications'. Vol. I, Part I and II, 1985

[2] - : Minimum Aviation System Performance Standards - DGNSS Instrument Approach System: Special Category I (SCAT-I) RTCA/DO-217, Aug. 1993

[3] - : NATO Standardization Agreement (STANAG 4294), October 1991

[4] Brenner, M.A. : Implementation of a RAIM Monitor in a GPS Receiver and an Integrated GPS/IRS, ION GPS-90, Colorado Springs, USA, Sep. 1990

[5] Hartman, R.G., Brenner, M.A., Kant, N., Fowler, B. : Results from GPS / GLONASS Flight and Static Tests. DGPS '91, Braunschweig, Sept. 1991

[6] Brown, R.G., Kraemer, J.H., Nim, G.C. : A Partial Identification RAIM Algorithm for GPS Sole Means Navigation. ION-GPS '94, Salt Lake City, Sept. 1994

[7] Diesel, J.W. : A New Approach to GPS Integrity/Availability: Immediate Global Sole Means Without WAAS. ION-GPS '94, Salt Lake City, Sept. 1994

[8] Loh, R. : FAA Wide Area Integrity and Differential GPS Program. DSNS '93, Amsterdam, 1993

[9] Sturza, M. A. : Navigation System Integrity Monitoring Using Redundant Measurements. NAVIGATION, Journal of The Institute of Navigation, Vol. 35, No. 4, Winter 1988-89, pp. 483-501.

[10] Vieweg, S. : Integrity Monitoring and Failure Identification within an Integrated Satellite-/ Inertial Navigation System. PLANS '94 Las Vegas, April 1994

[11] Vieweg, S., Butzmühlen, C. : Solving Integrity Insufficiencies of SatNav Systems with Complementary Navigation Information, ION GPS Sep. 1995

[12] Aebersold, R., Vieweg, S., Speckels, J., Lipp, A. : Guide Paths among the Alps : Switzerland's Precision Landing Trials, GPS World, July 1995

[13] Dr. Haverland, M., Jageniak, S.: Robust GPs Phase Ambiguity Software for the calibration of critical Landing Equipment, IFIS 96, Braunschweig, June 1996

[14] Lipp, A.: Experiences Using Carrier-Phase Positioning for Flight-Path Measurements, IFIS 96, Braunschweig, June 1996

Alenia approach to EF2000 propulsion system flight test: methodology and test results

Lucio Bellero, Francesco Dogliatti and Claudio Girolami
ALENIA Flight Test
Strada Malanghero
10072 CASELLE TORINESE, ITALY

ABSTRACT

EUROFIGHTER 2000 is a single seat, aerodynamically unstable delta-canard fighter aircraft which embodies latest technologies in structures, systems, engine and avionics. The aircraft is powered by two EJ 200, a new engine specifically tailored to meet EF2000 mission requirements.
Eurofighter Jagdflugzeug GmbH consortium is the prime contractor for the development of the complete weapon system. It is composed of the four national aircraft companies involved in the program, namely British Aerospace (BAe), Daimler-Benz Aerospace (DASA), Alenia (ALN) and CASA .
Within this program, Alenia is tasked (among the other responsibilities) with the propulsion system development, that has been initially flight-tested by Alenia prototype DA3; it has been the first one fitted with the new EJ200 engines (built by Eurojet consortium). DA7, the second Alenia prototype, will be tasked (among other tasks like avionics/navigation testing) of final aircraft/engines performance verification.
The first phase of the development programme has been successfully completed and the following phase, with the uprated engines standard, is already in progress.
This paper summarizes:
- the overall EF2000 flight test philosophy
- the approach to EJ200 engine flight test, including relight
- test organization, test methods, flight test instrumentation, data analysis, data management
- early test results

0. LIST OF ACRONYMS

A/C	AirCraft
APU	Auxiliary Power Unit
ATF	Altitude Test Facility
DECU	Digital Engine Control Unit
ECS	Environmental Control Unit
EJ	EuroJet
EMC	ElectroMagnetic Compatibility
FCS	Flight Control System
FM	Frequency Modulation
FOD	Foreign Object Damage
FTI	Flight Test Instrumentation
HP	High Pressure
HPGU	Hydraulic Power Generation Unit
LP	Low Pressure
MHDD	Multifunction Head Down Display
OTC	Official Test Center
PLF	Power Level Flight
SDR	System Design Responsible
SPS	Secondary Power System
VGV	Variable Guide Vane
WUT	Wind Up Turn

1. INTRODUCTION

EUROFIGHTER 2000 (EF2000) is a single seat, aerodynamically unstable delta-canard fighter aircraft which embodies latest technologies in structures, systems, engine and avionics. The aircraft is powered by two EJ 200, a new engine specifically tailored to meet EF2000 mission requirements (fig. 1).
This aircraft is the outcome of a common set of requirements issued jointly in 1985 by the Chief of Air Staff of United Kingdom (UK), Germany, Italy and Spain. This set of requirements, known as European Staff Requirement, defined a high performance, agile combat aircraft optimized for the air superiority role, capable of overcoming future threats. A secondary mission capability for air-to-ground attack was also required.
Eurofighter Jagdflugzeug GmbH consortium is the prime contractor for the development of the complete weapon system. It is composed of the four national aircraft companies involved in the program, namely British Aerospace (BAe),

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

Daimler-Benz Aerospace (DASA), Alenia (ALN) and CASA .
Within the worksharing Alenia is tasked (among the other responsibilities) with the propulsion system development.

2. TEST PLANNING AND MANAGEMENT

The management of flight test tasks allocated for propulsion system development is a challenging exercise, particularly for what concerns the definition of the tasks and their allocation within the programme time frame and with respect to the prototypes/flight test centres.
The master documents for the whole flight test activity are:

- the **Flight Test Programme**
- the **Flight Test Plan.**

These top level documents define the general architecture for EF2000 flight testing and include:

- the objectives of the development phase
- the philosophy of the tests
- the aircraft configurations (engines standard, external stores, airborne facilities ...)
- the list of engine development tasks
- the number of dedicated flights allocated to each prototype
- the characteristics of the envisaged facilities for each task
- the required instrumentation
- the structure of the telemetry control system

Those documents are issued by EF flight test group.

The detailed definition and description of all the required activities is included in the **Test Requirement** documents; these are written by flight test departments (according to the SDR) and then circulated before final agreement. The customer also can produce advisory comments.
Two requirement documents have been issued for EJ200 propulsion system and its related subsystems testing:

a) **EJ200 propulsion system**. Its objective is to verify and validate the engine integration with the EF2000 weapon system.
b) **Engine intake compatibility**. Its objective is to prove the compatibility of the intake throughout the flight envelope, the intake geometry control logic and the safe aircraft behaviour in case of engine surge and to validate recovery actions/pilot procedures.

Beyond those planning document, lower level documents are defined in order to allocate every flight test task to each prototype, including all the detailed information required for the completion of the task. These documents are also intended to define the suitable tasks beginning, their duration and the links (in terms of inputs/outputs) in order to have a smooth test progression towards the final system configuration.
These documents, again produced by the flight test groups according to the system SDR, are "living documents", updated several time to reflect actual programme status.

Routine output from flight test activities are collected, as usual, in the **Flight Test Reports**, issued after the completion of the relevant test campaign.
Quick document formats are also defined to circulate the snags and problems that (unlikely) could come out from the experimental activity.
Lower level snags will be eventually issued as **System Problem Reports**, to be circulated to all flight test centres and system SDR (the latter being in charge of a formal solution to the problem).
More severe problems will be eventually entered in **Occurrence Reports** and **Flight Safety Messages**, both under control of Airworthiness departments.

During planning of DA3 flight test it was recognized that the setting of a team of propulsion experts at Caselle flight test centre would be the most proficient way to manage the experimental activity.
Actual DA3 flight test team includes:

- flight test specialists
- propulsion system representatives (system SDR)
- EJ representatives
- customer technical specialists

The team has been early involved in detailed planning and coordinating both long term and day-by-day activities; now the team is analyzing, discussing and assessing the early results from experimental activity. This group has proven to be the right choice to guarantee the best proficient and efficient flight test of DA3.
Official interface meetings between Eurofighter and Eurojet are held every 2-3 months to check the status of the overall propulsion system activities.

A software tool has been developed by Alenia flight test in order to manage the phasing of the engines delivery and their allocation with respect to the prototypes activity.
Basic assumption for this simulation program is to assign an adequate number of engines to fully cover prototype activity.The software is designed to be modular in order to ensure a full coverage of the EF2000

programme (including post-development phase), both in terms of number of engines and in terms of time interval; time unit is 1 month.
Inputs to the software are the engine delivery dates and prototype flight periods; it is then possible to simulate all possible scenarios by entering different prototypes flight rates and engine allowed flight hours between overhauls (the software allows also to assign increasing engine operating hours during the program to reflect real engine clearances).
Software provides both quick-look overall graphic output on the screen (with the facility to zoom over a selected period) or output files compatible with most of the spreadsheets and word processors. The software proved to be useful to harmonize engine/prototype planning for the programme. An output sample of the software is shown in fig. 2.

3. TEST METHODOLOGY AND TECHNIQUE

As DA3 is a new aircraft to be flown with engines that never flew before (DA1 and DA2 were equipped with RB199 engines), Alenia chosen philosophy was aimed at minimizing any hazard from flight test.
Special care was devoted to bench, rig and ground test to gain all possible experience on the aircraft behaviour as a whole before real experimental flight test phase.

Relevant ground testing included:
- about 3000 test hours on the bench (including testing in ATF facility) before prototype first flight
- integration test on the aircraft with the other systems (including EMC)
- engine ground run
- surge interaction test
- taxi run

Main propulsion system dedicated flight test activities included:
- engine/aircraft shakedown
- engine handling from mild to more severe manoeuvres (including reslams from max reheat)
- engine subsystems verification
- idle schedule checks
- tip clearance test
- infrared signature
- engine in flight relight

Besides dedicated activity care was also taken to gather all possible useful data for propulsion system by ride along technique; data regarding engine vibration, fan flutter, air intake compatibility were planned to be acquired during test devoted to other disciplines.

A significant contribution to the successful engine development was the maintenance schedule, that was designed in order to timely detect any possible failure within the engine. It consisted of:
- daily inspection to all major engine component
- health monitoring and failure data downloading from DECUs memory into a Personal Computer after every engine run or flight.

GROUND TEST

Prior to beginning the flight test activity, a huge number of ground tests were carried out, aimed at ensuring that all critical systems were qualified for a safe, successful first flight of EF2000/DA3. These tests consisted of engine runs and aircraft systems checkout (SPS, ECS, Electrical, Hydraulic).
These tests were carried out in ALN hush house as well as on external engine run pad. Cleanliness was deemed essential during these tests to avoid any FOD risk.
The most relevant test performed on ground were the following :
Single/double engine start via APU and cart;
Engine start via cross bleed;
Engine reheat light up and leaks checks;
Engine dry and reheat ratings checks;
Engine handling checks;
Engine load checks (aircraft surfaces movement during engine stabilizations and handling).

EMC tests were carried out during this phase to demonstrate that all aircraft systems and subsystems (including instrumentation) were electromagnetically compatible within the aircraft.

As a part of the first flight clearance procedure for EF2000 fitted with EJ200 engines, ground surge interaction trials were conducted:
- to provide experimental data for comparison with design data.
- to verify the design of the air intake, that was aimed to minimize any effect on the other engine when the other one is surging.

The test technique consisted of provoking a surge on one engine while the other was running at the typical rating of landing or take-off. Surge was induced by loading a modified schedule in the DECU of the surging engine. Uniquely for these surge interaction trials, special fast response pressure transducers were flush mounted to the external skin of the prototype.
Low and high speed taxi tests were planned to verify the aircraft taxi speed at idle and

aircraft/engine handling as close as possible to the rotation speed.

FLIGHT TEST

shakedown flights

One of the primary objectives of this phase of flight testing was the preliminary verification of the propulsion system and its integration within the aircraft when airborne.

Dedicated test points were planned to gather initial data about the engines EJ200/01A correct functioning as well as engine/intake compatibility. Test points consisted of stabilizations with engine power set for straight and level flight followed by either a wind up turn or slow down.

No dedicated engine handling manoeuvres were planned and both the engines were requested to be always modulated gently and symmetrically. Beyond these test points, all flight test activity was planned to gather initial data on a ride along basis about propulsion, mechanical systems, avionics, flying qualities, performance and instrumentation correct operation.

Brief emergency procedures, brief “keywords”, safety chase and a careful monitoring of the engine parameters by the real time test team, were defined to perform these first flights minimizing any possible hazard.

engine development flights

The objective of subsequent phase of flight testing was the propulsion system EJ200 standard 01A development.

All tests were performed at Alenia Flight Test Center, Caselle.

Steady state, transient and TIF (Thrust In Flight) decks were made available by EJ in order to have predictions about engine behaviour as well as to compare engine performance with design requirements. The thrust of the EJ200/01A engine was derived from flight test data by using a calibrated performance computer deck. This program contained a generic model of 01A family which, by using an individual calibration data set derived during the engine’s pass off test, could be factored to reflect any particular 01A engine installed on the aircraft. Engine decks allowed timely simulation of planned test points directly at flight test centre.

Engine deck was also integrated in the EF2000 flight simulator. This provided the pilot with a useful tool to assess overall best test techniques and procedures.

Here in the following a list of engine dedicated tasks is detailed:

- Assessment of dry and reheat engine handling

Planned test points began with slow/mild dry engine modulations (stepwise modulations in dry range followed by slow accelerations IDLE-MAX DRY and slow decelerations MAX DRY- IDLE) and progressed to more severe manoeuvres up to slams, chops and reslams between IDLE and MAX RHT.

Engine stabilization was required prior to starting each maneuver and after its completion. All maneuvers were performed on each engine in turn, with the non-test engine set to maintain the required flight conditions.

Compressor working lines and air intake pressures were chosen for real time monitoring of engines and provided a clearance towards more demanding test points.

- Assessment of engine idle schedule

Scope of this test was to evaluate idle stability and sensitivity to speed and altitude.

The technique consisted of a series of aircraft decelerations at constant altitude, aircraft descents at constant Mach and aircraft descents at constant airspeed with both engines set at idle.

- Assessment of engine oil sub-system

The dedicated test profiles consisted of a series of rollercoasters (single, double, triple) performed at different flight conditions and engines setting up to the allowed g limits.

Three different combinations of engine settings were planned for each manoeuver: both engines as requested for PLF (part dry); left/right engine at max dry with the other as requested for PLF. Particular attention was paid to maintain, during each maneuver, a fixed throttles position.

- Tip clearance test

Aim of this test was to verify the clearance of LP/HP rotors blades with respect to engine casing at the maximum allowed load factor. The target test profile consisted of a WUT up to the maximum allowed load factor, with one engine at max dry and the other at PLF setting.

Some WUTs were performed at lower g as a build-up towards the target. The required engines setting was maintained for about 3' prior to starting the WUT; this was done in order to achieve a steady engine condition before the test. Particular attention was paid not to move the throttles during the entire manoeuvre, from the start of the stabilization to the end of the WUT. In this way no other possible source of stress to the engine, apart from the g-load, was induced.

The WUT were performed at the end of each related flight, then avoiding any further rapid throttle movement up to the aircraft landing.

Analysis of abradable material in the compressor case with boroscopes after each relevant test provided the clearance towards more severe maneuvers.

-Infrared signature

Early infrared measurement was a firm requirement by the customer. The chosen technique was tower fly-by's passes in front of a ground-based measurement system provided by the customer.
Predictions, simulations and in-flight verification of the best technique were planned to achieve the requested test conditions (to fly at a definite distance from the measurement device with stabilized engines setting at a definite speed).
As measurement system was available only for a limited amount of time, tests were planned at a remote airfield not to have any constraints from civil traffic in Caselle airport.

- Engine in-flight relight

Flight trials as severe engine handling in envelope corner points, missile firing and high incidence trials could involve the risk of engine flame out.
In order to perform these tests with the confidence that the engine could be (if necessary) successfully relit, it was planned to carry out dedicated in-flight engine relight test in the early phase of development programme.
This relight campaign was aimed at verifying the immediate and windmill relight capability characteristics of the unloaded EJ200 engines to validate the relight envelope released by EJ.
One engine needed to be deliberately shut down to perform these tests in flight; this action reduced A/C redundancy in terms of primary power source.
The risk of a double engine flame out in this condition was then assessed in accordance with System Safety Assessment and classified within the "unacceptable high risk" category. This, in turn, required some alternative solution to allow test execution.
An emergency power source proved to be a good solution of this problem. The use of the APU operative in flight was chosen among a number of alternatives. Some modification were defined to allow APU use during flight, being the baseline configuration designed for ground operation only.
These modifications mainly involved the SPS hardware and software. Both ground and in-flight verification of this configuration were planned before starting the relight trials. Moreover, care was taken to maximize the safety level of this tests by means of dedicated normal/emergency procedures.
Dedicated sessions were planned at the aircraft simulator, that was specially configured for these trials.

The relight test were planned to begin in the most favourable portion of the predicted relight envelope and proceeding towards more critical condition.
In the early phase no power off-take or assisted relight capability tests were planned.

Ride along test

- Ground starts

Every relevant aircraft test was intended as useful for engine ground start sequence check. This gave the opportunity to verify the complex interface between engine and aircraft systems in this phase.

- Assessment of engine/air intake compatibility

EF2000 is designed with variable intake lip, scheduled to optimize air intake geometry with respect to actual flight conditions; DA3 is also equipped with manual intake lip control to evaluate the effect on the engine of lip offset.
Evaluation of engine/intake compatibility was based on pressure measurements in the air intake, at engine face and by compressor working lines.

- Assessment of fan flutter and engine vibration

During all engine starting and the bulk of the flight trials, EJ high frequency parameters were recorded using FM single track technique on the on-board magnetic recorder.
As FM signals with high frequency contents would eventually require too high sampling rate both for on-board recording and for telemetry downlink, conditioner boxes were designed by ALN flight test for real time monitoring of engine vibration. Output from the boxes were one-sided envelopes of the original analogue signal, to be transmitted to the ground station for comparison with reference level.
This technique was designed to speed-up the analysis process, as specialists were able to identify the maneuvers to be analyzed even during the test.

- Engine bay ventilation

Engine bay ventilation assessment was planned on the basis of bay temperatures assessment. This activity was planned on a ride along basis by means of real time monitoring of relevant parameters.

- Engine subsystems

This task includes Air Flow Control System (AFCS) and Fuel Cooled Oil Cooler (FCOC).
The conditions defined for the assessment of the AFCS were: engine operating at steady state, engine transients, normal load factor variation.
Real time monitoring technique was chosen to check the AFCS relevant hydraulic pressures and temperatures.

The conditions defined to assess the FCOC are: engine stepwise stabilizations, IDLE to MAX DRY; throttle slams and chops, IDLE decelerations (constant altitude), IDLE descents (constant KDAS), MAX DRY climbs.

4. DATA ACQUISITION SYSTEM

FTI data are recorded on a magnetic tape recorder onboard the aircraft.
A set of parameters is simultaneously transmitted to the ground telemetry station for recording, real time analysis, and control room monitoring. Digital data from aircraft busses are recorded directly, while parameters such as engine temperatures and pressures are first converted to voltages by appropriate transducers, then conditioned and formatted.
EF2000 is the first ALN programme to make extensive use of aircraft bus data for FTI purposes. This approach results in a lower cost for FTI installation and provides the engineering team with the same data that are sent to the pilot and to the on-board equipments: more accurate analysis can be performed.
Nevertheless, this philosophy prompts for a careful approach to the problem in terms of:
- FTI physical interface with the busses (a non-intrusive one have to be chosen)
- dataset generation and management for programming the parameters to be extracted from the busses (a unique dataset had to be agreed among the companies for data exchange)
- Time tagging of bus data with respect to FTI data.

The DA3 onboard data acquisition system uses both pulse code modulation (PCM), and frequency modulation (FM) for data encoding. The FM technique is used for high frequency signals, provided via EJ crates. A dedicated interface is available on aircraft for detailed FTI check immediately before the test; thanks to this facility, no tests up to now have been cancelled due to instrumentation problem.

Real time monitoring and real time data analysis is used throughout this programme in order to speed-up the clearance process to the next flight and to minimize flight test time by giving "real time clearances" towards more demanding test points.
This target is achieved mainly by means of:
a) Specifically tailored real time graphical displays. Alenia standard control room facility consists of 7 work stations, each provided with a high resolution video display. Graphical menus have been developed and optimized during early ground testing phase to provide the control room team with the capability to monitor almost all the relevant engine schedules (figg. 3-4).
Colour printers are connected to the displays with the possibility to print in each moment the displayed parameters. In the upper part of the station some digital displays (in numerical, bargraph and light forms) are available, too. Some 8 channel strip chart pen recorder and ES2000 high resolution, 24 channel, electrostatic recorders, with printers, are also available.
b) "quasi real time analysis" (QUARTAS) by means of temporary memory areas. Real time team can store a number of telemetered parameters referred to significant manoeuvers allowing their analysis immediately after test point execution .

5. TEST RESULTS

GROUND TEST

All major activities planned have been successfully achieved. Propulsion system behaviour was good overall. Engine exhibited satisfactory, stable operation and good transient characteristics both in dry and reheat range. Engine/aircraft interfaces performed as expected and no limits were exceeded. No FOD were encountered during these tests thanks to the clean environment.

- Surge interaction test
Three surges were induced during the test. Engine behaviour between two consecutive surges showed that it attempted to self clear the surge. Recorded overpressure ratio was in accordance with intake hammershock limit figure (see fig. 5).
Fast response transducers showed that only a small disturbance entered the adjacent engine from the surging one. Only low pressure fluctuations were observed, but engine behaviour was not affected at all.

TAXI TEST

Test indicated a prompt response of the engine and an impressive aircraft acceleration, even with internal tanks full.
The test were carried out with both engines running and symmetrically operated, over both dry and wet runway. After 10 low speed and 5 high speed test, the aircraft was cleared for first flight.

FLIGHT TEST

The initial assessment of EJ 200 engine, 01A standard, was successfully completed in 6 shakedown flights and 34 experimental flights.

During this phase of flying 2 Alenia test pilots and 1 OTC test pilot have flown DA3 prototype, accumulating about 38 flying hours.

The bulk of the trials were dedicated to engine development and propulsion system assessment.

About 70% of effective aircraft test time was devoted to engine development tasks.

In addition, a considerable amount of propulsion system related data have been collected on a ride along basis during aero-mechanical manoeuvres.

The engines have been thoroughly tested throughout the initial flight envelope.

Post-test analysis showed that demands as a function of engine and flight condition have been correctly computed and actual position and values were precisely obtained and maintained.

No sign of instability was noted.

DECU-FCS integration was very good.

shakedown flights

Correct functioning of propulsion system and its integration within the aircraft was successfully carried out either by means of dedicated test points or ride along. No significant problems were highlighted from these tests.

These initial trials prepared a "checked out" test aircraft ready to conduct the next phase of testing.

Engine development flights

- Dry Engine Handling

Dry engine handling manoeuvres were performed on each engine in turn.

About 20 slow/mild engine modulation sequences were performed, followed by slam/chop sequences throughout the allowed envelope.

Maneuvers up to the maximum allowed angle of attack were carried in the course of these tests.

The DECU's maintained satisfactory control of the engines throughout the handling tests. Both engines exhibited good transient characteristics and no overshoot/undershoot of any engine parameter was observed.

Engine response to throttle transients was reported as prompt and smooth. Required settings were obtained easily and with precision. Transient times were as expected.

Neither engine surges nor stagnations were experienced during the trials.

The behaviour of actual engine parameters during transients was in good agreement with simulation deck predictions.

No sign of instability was detected during steady state engine operation.

- Reheat Operation and Handling

Reheat operation was successfully assessed, both during dedicated trials and in the course of tests devoted to other subjects.

About 120 reheat operation cycles (from selection to deselection) were performed on each engine respectively both in subsonic and in supersonic range.

The DECU's maintained satisfactory control of reheat selection sequence and reheat operation throughout the trials.

Reheat light-up was always successful and no uncommanded reheat shut-down occurred. Both engines proved good transient characteristics and no overshoot was observed. No engine surge was experienced and jet pipe buzz screech levels remained always well below the limits.

- IDLE schedule

HP spool speed (NH) idle schedule was assessed throughout the tested envelope during both dedicated and ride along manoeuvers.

Throughout the trials the DECU maintained excellent control of the engine. NH always matched the schedule and no undershoot was observed. No instability was detected either.

- Engine Subsystems

Test points dedicated to oil system assessment were carried out at different flight conditions and engine settings. No appreciable influence of load factor on oil system functionality and performance was observed.

No anomalous engine subsystem behaviour was detected throughout the considered phase of flying. Pressure and temperatures of the fluids (fuel, lubricating oil, hydraulic oil) remained always within the relevant limits.

- Tip Clearance

A total of 4 manoeuvres dedicated to assess tip clearance of compressor/turbine blades were carried out up to the maximum allowed "g".

No engine malfunction occurred during these manoeuvres. No sign of mechanical interference on both static and rotating engine components was detected by post-flight inspections.

- Infrared signature

Preliminary flights were carried out to obtain the best possible accuracy in the trajectory with respect

to the measurement station; this was achieved by using GPS data. Tracking informations and synchronizing signals were sent from the telemetry station both to the pilot and to the operators in the measurement station. Pilot also had a dedicated route loaded into the MHDD.
Thanks to this approach, infrared measurement program was carried out in the planned period and was concluded in two days with about 30 successful fly-bys.
Data were successfully acquired and allowed an assessment of aircraft infrared signature in all the infrared spectrum and the definition of the most intense radiation sources and their visibility.

- Engine start sequence
Engine behaviour during start was assessed using all possible power sources, i.e. external cart, APU or crossbleed from the other engine.
Single and double engine start were performed and the results are as expected.
Engine sequence was always successful.

- Engine Vibration and Fan Flutter
Analysis carried out by EJ specialists on vibration and fan flutter signals showed that these parameters always remained well below the relevant limits.

- Engine/Air Intake Compatibility
As far as engine/air intake compatibility is concerned, no sign of incompatibility was noted during the considered phase of flying. Air Intake Control System (which is part of FCS) operation was excellent throughout.

- Engine Bay Ventilation
Air temperature values measured in the engine bays always remained well below the design limits.

- AFCS/FCOC
The AFCS behaviour under engine steady state conditions was evaluated during engine stepwise stabilizations.
The AFCS performed as expected throughout the conditions tested. No abnormal AFCS behaviour was detected. The system correctly and promptly reacted to DECU requests of nozzle and/or VGV movement, being capable of actuating the nozzle against the loads achieved during the tests while at the same time actuation of the VGV was taking place.
AFCS behaviour under engine transient conditions was evaluated during throttle slams and chops.
Data from stepwise engine stabilizations were superimposed on the plots, showing good correlation between transient and steady state behaviour of the AFCS parameters.
In order to assess the continuity of the HPGU supply pressure, a survey was then conducted analyzing the maximum nozzle area variation rate during the slam/chop in all the conditions tested. This was considered the worst condition for the HPGU as far as supply pressure drop was concerned.
Load factor effect on AFCS behaviour was evaluated during triple rollercoaster manoeuvres.
No direct influence of load factor was evident from the analysis.
FCOC performed as expected throughout the conditions tested. No abnormal FCOC temperatures were achieved.

6. CONCLUSIONS

The initial part of EJ200 engine development has been successfully achieved on EF2000 DA3 prototype. Initial standard of the engine (01A) has been tested both on ground and in flight throughout the allowed envelope.

The results were excellent, as:
- engines response and behaviour were according to the predictions.
- engines were integrated in the EF2000 aircraft without any significant interface problem.
- no siginficant problem occurred during the whole testing, too.

This was the result of a comprehensive approach to the flight testing phase by ALN flight test team. Integration among all the involved departments from Eurofighter EPCs, Eurojet and the customer was a key factor to the success of this initial flight testing on DA3.

Extensive use of real time monitoring and analysis proved to be a key factor for speeding up the whole flight testing process and for fast clearance towards the targets. This was a result of a careful planning of the test techniques and their analysis flow.
Some minor snags were highlighted by the test, thus allowing a timely recovery for the continuing of the development.
Upon completion of this first test campaign, DA3 already began the development of EJ200 01C standard.

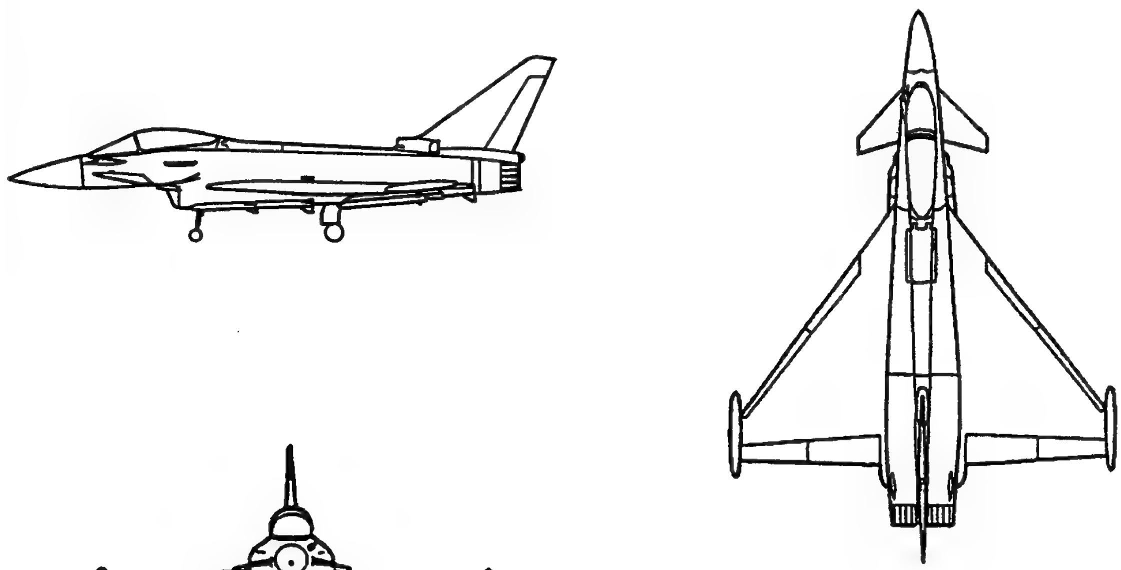


Fig. 1 - EF2000 general layout

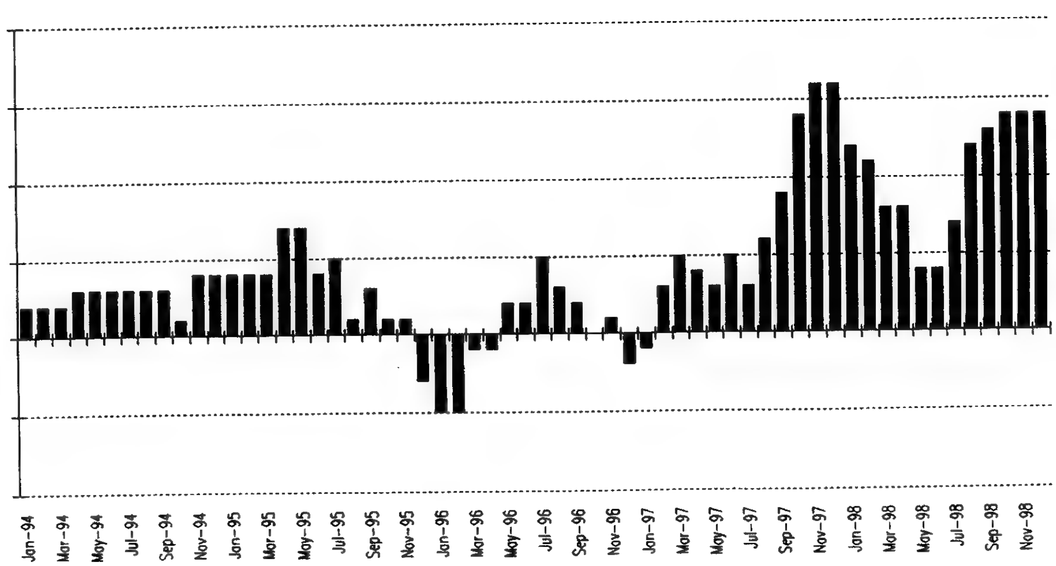


Fig. 2 - Engine allocation simulation output

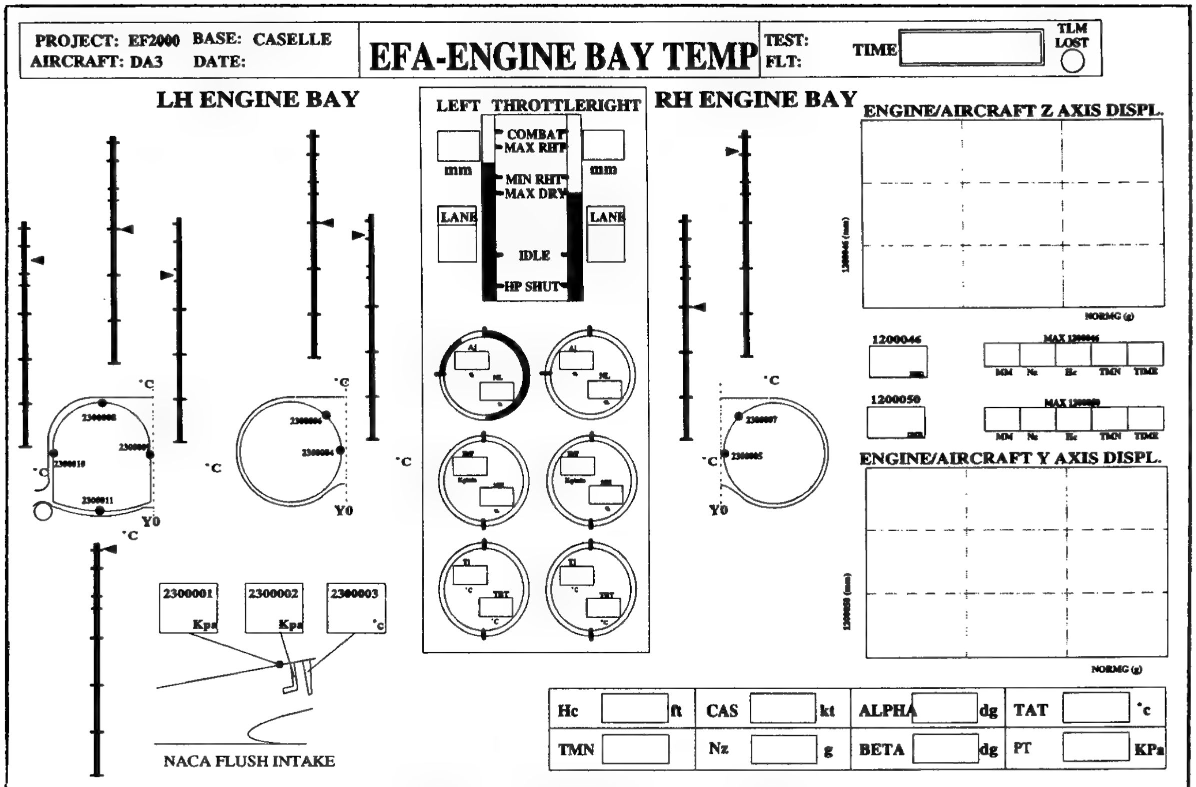


Fig. 4 - Engine bay temperature real time display

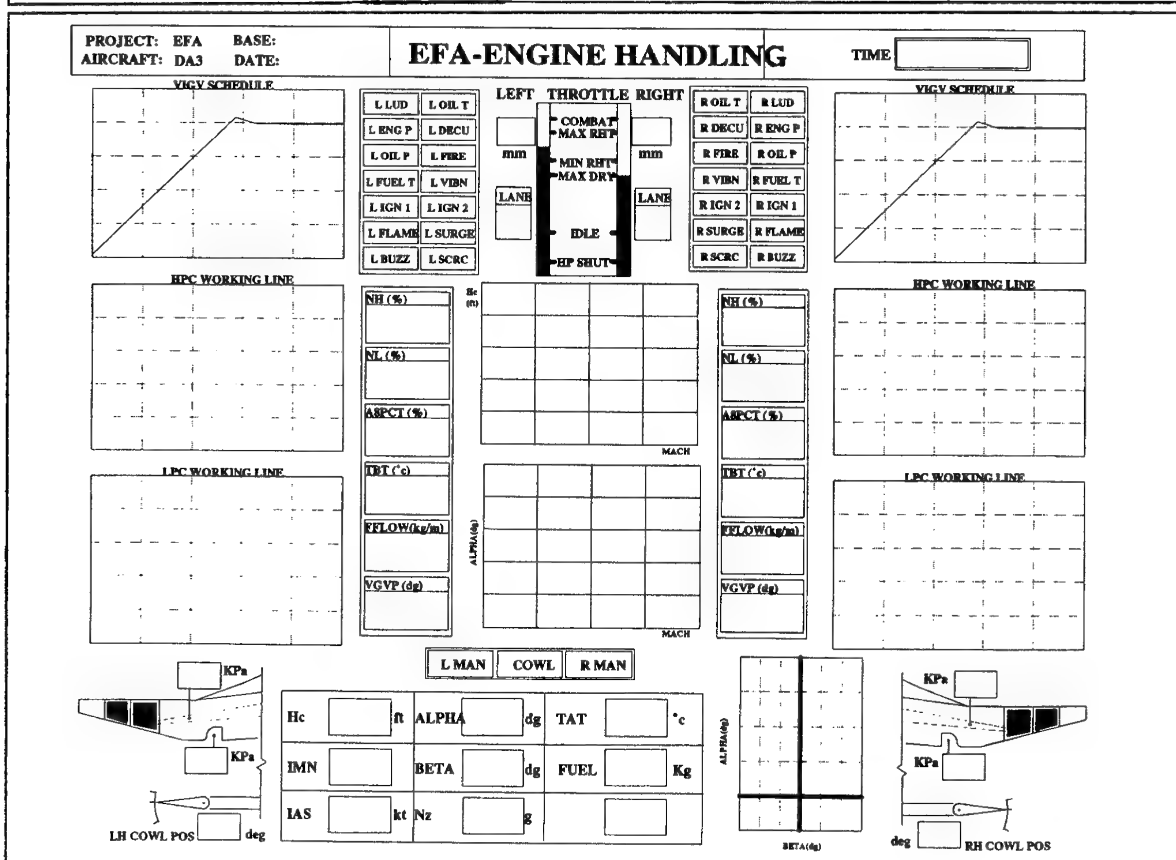


Fig. 3 - Engine handling real time display

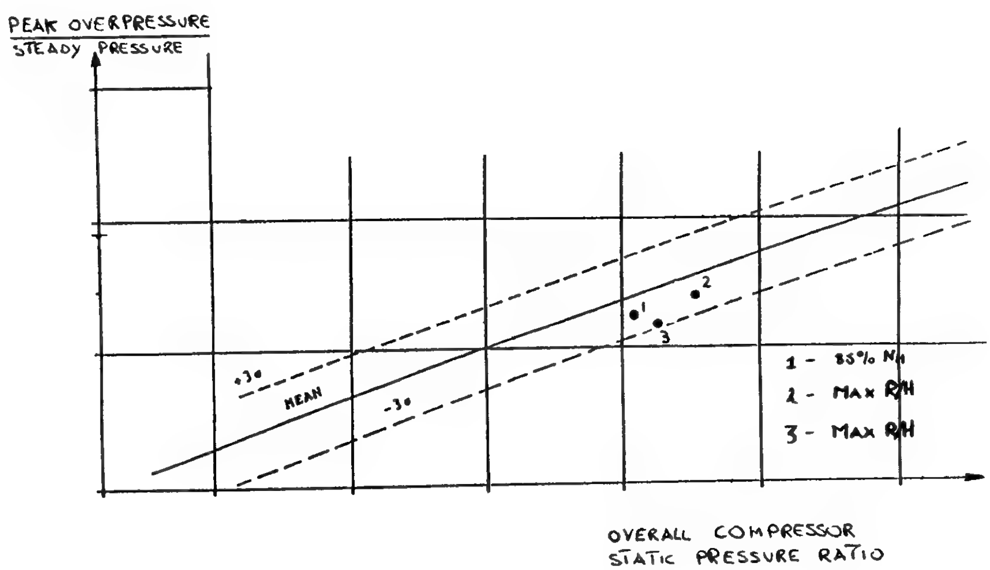


Fig. 5 - Measured overpressure ratio

BON DE VOL M 88-2

par

Eric NICOLET
Centre d'Essais en Vol
Base d'Essais d'Istres
13128 Istres Air
France

RESUME

Le M88-2 est le moteur équipant l'avion de combat polyvalent Rafale. La méthode de qualification en vol de la régulation consiste à réaliser un moteur représentatif du plus mauvais moteur produit en série et de vérifier que celui-ci à un comportement sain dans l'ensemble du domaine de vol.

1. PRESENTATION DU M88-2

Le M88-2 est un moteur double corps, double flux avec post combustion sur les deux flux développant une poussée au plein gaz de 4.8 t et de 7.5 t en pleines charges PC. Sa régulation est de type FADEC assurée par deux calculateurs numériques.

1.1 DESCRIPTION DE LA VEINE

Le moteur est constitué des éléments principaux suivants :

un compresseur basse pression axial à 3 étages avec directrice d'entrée dégivrable à calage variable,

un compresseur haute pression axial à 6 étages avec directrice d'entrée et redresseurs des deux premiers étages à calage variables. Le prélèvement d'air avionneur est disponible en sortie du 6ème étage,

une chambre de combustion annulaire à 16 injecteurs et équipée d'une bougie d'allumage,

une turbine haute pression mono-étage,

une turbine basse pression mono-étage,

les deux corps basse et haute pression sont supportés par 5 paliers au total.

le dispositif de post combustion se compose de :

un bougie d'allumage,
9 crayons amonts et 9 bras équipés de crayons dans le flux primaire,
un anneau brûleur dans le flux secondaire.

une tuyère simplement convergente comporte 10 paires de volets chauds actionnés par 5 vérins.

1.2 PRINCIPES DE LA REGULATION

Le système de régulation est composé de deux calculateurs numériques à logiciels identiques, dialoguant entre eux, et des actionneurs hydromécaniques. Ce système régule les paramètres suivants :

régime de rotation du compresseur basse pression par action sur le débit de carburant principal,

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

étranglement du compresseur haute pression par action sur la tuyère,

débits de post combustion injectés dans les flux primaires et secondaires.

position de la roue directrice d'entrée du compresseur basse pression,
position des stators du compresseur haute pression.

Le système assure en outre :

les fonctions
de la surveillance automatique du démarrage,
du rallumage automatique en sec et en PC.

les limitations :
température turbine maximale en agissant si besoin sur l'ouverture de la tuyère,
régime basse pression maximal,
régime haute pression minimal et maximal,
pression chambre minimale et maximale en agissant sur le débit carburant.

L'ensemble des lois de régulation est élaboré de façon redondante par les deux calculateurs qui reçoivent et traitent tous les signaux en provenance de l'avion et du moteur et élaborent les consignes de régulation.
Ces deux calculateurs dialoguent entre eux, se communiquent leurs résultats de calculs et choisissent le calculateur actif qui commande les différents actionneurs :

doseur sec et électro-robinet stop,
vérins de tuyère,
vérin roue directrice d'entrée,
vérins stators,
doseurs PC, électro- robinet stop PC et électro- robinet crayons PC.

En cas d'anomalie détectée par le système de régulation sur les paramètres d'entrée en provenance de l'avion ou du moteur, celui-ci se reconfigure dans différents mode dégradés signalés ou non au pilote en fonction de la diminution des performances que le fonctionnement de ce mode entraîne.

2. MOYENS D'ESSAIS UTILISES

2.1 LE SITE D'ESSAIS

Les essais se sont déroulés sur la Base d'Essais d'Istres à l'ouest de Marseille. Les zones aériennes associées permettent une exploration rapide de l'ensemble du domaine de vol : de la montée perfo à 50000 ft à l'accélération supersonique à basse altitude.

2.2 AVIONS BANC D'ESSAIS

Les essais en vol se sont déroulé sur deux avions banc d'essais : le Rafale A équipé d'un moteur GE F404 et d'un M88-2 qui a effectué 391 vols du 9 mars 1990 au 23 décembre 1993 et le Rafale C01 équipé de deux M88-2 qui a effectué 528 vols du 24 mars 1992 au 24 janvier 1996.

2.3 SUIVI TEMPS REEL DES ESSAIS

Les essais sont conduits et exploités en temps réel en salle d'écoute par exploitation du message transmis par télémesure.

3. EPREUVE DU BON DE VOL

L'épreuve du bon de vol permet de vérifier le bon fonctionnement du moteur dans une définition correspondant au cas le plus défavorable prévu pour la série, par suite des dispersions de fabrication et de réglage.
Cette épreuve ne couvre que les limites de fonctionnement gérées par la régulation. Toutes les autres validations du moteur (mécaniques, dynamiques, thermiques, performances ...) sont réalisées par ailleurs.

3.1 LA METHODOLOGIE

La méthodologie du Bon de Vol est de réaliser, par risque de dysfonctionnement, un moteur dont la marge est la plus faible compte tenu du parc des moteurs de série. La définition de ce

moteur, appelé moteur extrême, et la simulation par déréglage de moteurs représentatifs de ce moteur extrême sont les points déterminants dans la réussite du Bon de Vol.

La méthodologie est la suivante

1 identification des risques,
2 définition des taux de couverture,
3 détermination du déréglage,
4 détermination du moteur moyen,
5 réalisation du moteur extrême,
6 réalisation des manoeuvres à risque maximales sur les moteurs extrêmes.

3.1.1. IDENTIFICATION DES RISQUES

La régulation du moteur est optimisée de manière à fournir les performances maximales tout en maintenant le moteur dans ses limites de fonctionnement afin d'éviter tout dysfonctionnement.

Parmi les risques de dysfonctionnement d'un moteur, l'expérience acquise pendant le développement ainsi que l'analyse des principes de la régulation ont conduit à retenir les risques suivants :

décrochage des compresseurs haute et basse pression,
blocage et dévissage du compresseur haute pression,
extinction de la chambre de combustion,
rallumage-redémarrage,
extinction de la post combustion,
non allumage de la post combustion.

3.1.2. DEFINITION DES TAUX DE COUVERTURE

En fonction de leurs conséquences sur le fonctionnement du moteur, les risques sont classés en 3 catégories :

risques conduisant à une situation critique : non allumage de la chambre dans le domaine de rallumage,

risques imposant une action du pilote, par exemple le décrochage du compresseur haute ou basse pression,

risques n'imposant pas une action immédiate du pilote, par exemple le blocage de régime.

A chaque catégorie est associé un taux de couverture décroissant.

3.1.3. DETERMINATION DU DEREGLAGE

Pour déterminer les déréglages on va dans un premier temps évaluer la dispersion des moteurs de série puis en déduire, en fonction du taux de couverture choisi, le déréglage à réaliser pour réaliser la marge du moteur extrême.

3.1.3.1 évaluation de la dispersion

On détermine pour chaque risque l'ensemble des paramètres influents en les classants en deux catégories :

les paramètres déterministes dont l'influence est quantifiée,

les paramètres aléatoires dont l'influence n'est pas quantifiée mais obéit à une loi normale.

Les paramètres aléatoires ayant une distribution régie par une loi normale, la dispersion de marge au point critique est la somme des contributions individuelles qui est elle même une variable aléatoire régie par une loi normale.

L'empilement de ces dispersions permettra de définir la dispersion des moteurs et de déterminer la marge du moteur extrême au cas critique.

Prenons l'exemple du risque décrochage du compresseur haute pression (7.7)
On représente dans le champs intrinsèque taux de compression débit réduit la ligne de pompage et le trajet sur la butée d'accélération.
On détermine pour cette première :

les effets déterministes : viscosité, thermique, distorsion, traînage des stators,
les effets aléatoires : qualité du compresseur haute pression et calage des stators.

On fait de même pour le trajet sur la butée d'accélération :

effets déterministes : viscosité, thermique, distorsion, traînage des stators, prélèvements de puissance, prélèvement d'air, densité du carburant,
effets aléatoires : qualité des composants, calage des stators, mesure de la régulation et réalisation de la commande.

3.1.3.2 Détermination du déréglage.

Ayant déterminé la dispersion des moteurs des série on déduit la dispersion à couvrir en fonction du taux de couverture choisi. Ce déréglage sera appliquer au moteur moyen pour réaliser le moteur extrême.

3.1.4 CHOIX DU MOTEUR MOYEN

Afin d'estimer les caractéristiques du moteur moyen on va caractériser un échantillon de moteurs vis à vis de chacun des risques retenus.

On distingue deux catégories de risques :

les risques pour les quels il est possible de mesurer l'écart à la limite (pompage du compresseur HP et BP, blocage dévissage),
les autres pour les quels cela n'est pas possible.

Pour les premiers, on effectue un classement des moteurs de l'échantillon ce qui permet de déterminer l'intervalle de confiance de l'estimation de la moyenne. Le moteur moyen sera pris sur la limite basse de cet intervalle (7.8).
Pour les autres risques, les moteurs de l'échantillon seront simplement triés, c'est à dire positionnés les uns par rapport aux autres et le moteur moyen sera le plus mauvais de l'échantillon (7.9).

Voyons sur deux exemple une méthode declassement et une méthode de tri.

Afin de limiter le nombre d'essais en vol, les classements des risques décrochage du compresseur HP et BP ainsi que le risque de blocage dévissage ont été réalisés au sol avec une confirmation en vol sur quelques points d'essais. Les autres risques ont été triés en vol.

Par exemple la méthode de classement au sol du décrochage du compresseur HP a consisté à placer la ligne de pompage du moteur dans un champ taux de compression débit réduit à partir de la reconstitution de la trajectoire du point de fonctionnement en transitoire lors d'un échelon de carburant. L'échelon de carburant est progressivement augmenté jusqu'à apparition du pompage. Afin d'éviter un pompage intempestif du compresseur BP, la tuyère est maintenue à une position fixe.

Pour le risque de non allumage de la PC, on a réalisé des allumages PC simples (plein gaz sec-ralenti PC) à n=1 en ouvrant progressivement la tuyère jusqu'à ce que la PC s'allume tardivement. Etant donné que l'ouverture de la tuyère au delà de sa position régulée entraîne une variation de la richesse PC, cet essais est repris en modifiant celle-ci. De plus pour être sur d'allumer sur des débits stabilisés on a temporisé le claquage de la bougie d'allumage de la post combustion. Ces essais permettent de positionner les moteurs dans un champ richesse pression de sortie flux secondaire et de déterminer le plus mauvais moteur.

3.1.5 REALISATION DU MOTEUR EXTREME

Le moteur extrême est obtenu en appliquant à ce moteur moyen le déréglage précédemment obtenu.

Les déréglages sont réalisés en déréglant les lois de régulation des paramètres dimensionnant pour chaque risques. Par exemple pour le décrochage du compresseur HP on déréglera la butée d'accélération pour simuler une diminution de marge ainsi que le calcul de la densité du carburant pour tenir compte d'un

carburant lourd. Ces déréglages sont réalisés en temps réel par le pilote qui dispose en cabine d'un boîtier "TRIM" (7.10) associé à chaque moteur. Ce boîtier permet de modifier simultanément 5 paramètres parmi les dix programmés pour le vol. Un mnémonique de chaque paramètre modifiable s'affiche dans les écrans de visualisation avec en face le nombre de pas de modification que le pilote affiche en utilisant les clés de droite. Les clés de gauche permettent d'activer et de désactiver les trims. Cette désactivation et activation est également possible par une commande temps réelle située sur la commande des gaz et n'est active que lorsque l'avion est en configuration essais moteurs. Ces boîtiers ont également servi à la mise au point du moteur. Pour des raisons évidentes de sécurité, un seul moteur est déréglé à la fois

3.1.6. REALISATION DES MANOEUVRES A RISQUE MAXIMALES SUR LES MOTEURS EXTREMES.

L'ensemble des opérations précédentes permettent de déterminer les déréglages à appliquer pour chaque risque. Ceux-ci sont donnés pour chaque point de vol à réaliser et le pilote déréglera un moteur à l'extrême en utilisant le boîtier trim. L'épreuve du bon de vol consiste à réaliser sur les moteurs ainsi déréglés les manoeuvres à risque maximum.

On classe ces manoeuvres en deux catégories :

- les manoeuvres moteur : mouvements de manette de gaz,
- les manoeuvres avion : comme la prise d'incidence, dérapage ...

A chaque risque moteur est associé une ou plusieurs manoeuvre à risque maximum. Ces manoeuvres "élémentaires" permettent de reconstituer l'ensemble des mouvements de manette susceptibles d'être réalisés par un pilote opérationnel.

Pour le décrochage du compresseur HP on a effectué des manoeuvres du type :

- reprises : régime intermédiaire ↗ plein gaz sec ou régime intermédiaire une ↗ pleine charge PC,
- agaceries : plein gaz sec ↘ régime intermédiaire ↗ plein gaz sec, plein gaz sec ↘ régime intermédiaire ↗ pleine charge PC ou encore pleine charge PC ↘ régime intermédiaire ↗ plein gaz sec.

Ces manoeuvre sont réalisées à n=1, incidence intermédiaire et maximale.

Pour le non allumage de la PC, les manoeuvres essayées sont :

- allumage simple : plein gaz sec ralenti PC,
- adf : plein gaz sec pleine charge PC,
- ADF : ralenti sec pleine charge PC.

De même ces manoeuvres sont réalisées à n=1, incidence intermédiaire et maximale.

La réalisation des manoeuvres à n=1 ne posent pas de problèmes particuliers. Par contre la réalisation des manoeuvres sous incidence maximale demande beaucoup de maîtrise de la part du pilote d'essais. Les déréglages varient avec le domaine de vol en diminuant avec la vitesse et la prise d'altitude. Les manoeuvres sont généralement réalisées à iso altitude et en diminution rapide de vitesse en haute altitude. Une manoeuvre réalisée avec un vitesse trop forte n'est pas assez critique alors qu'une manoeuvre réalisée avec une vitesse trop faible et cette fois trop critique. Dans les deux cas l'essais n'est pas représentatif. Le suivi en temps réel de l'essais permet immédiatement après l'execution du point d'essais de vérifier si celui-ci a été réalisé dans les conditions requises.

Essais des modes dégradés :

L'analyse de la régulation dans les modes dégradés permet de déterminer si la marge vis à vis du risque est plus importante qu'en mode normal. Si elle est inférieure ou s'il n'est pas possible de la comparer avec la marge de la régulation normale, les essais seront également réalisés en mode dégradés. Dans le cas contraire, l'essais en mode normal couvre le mode dégradé.

Les transitoires mode normal-mode dégradé et retour en mode normal (lorsque le mode est réversible) sont également essayés.

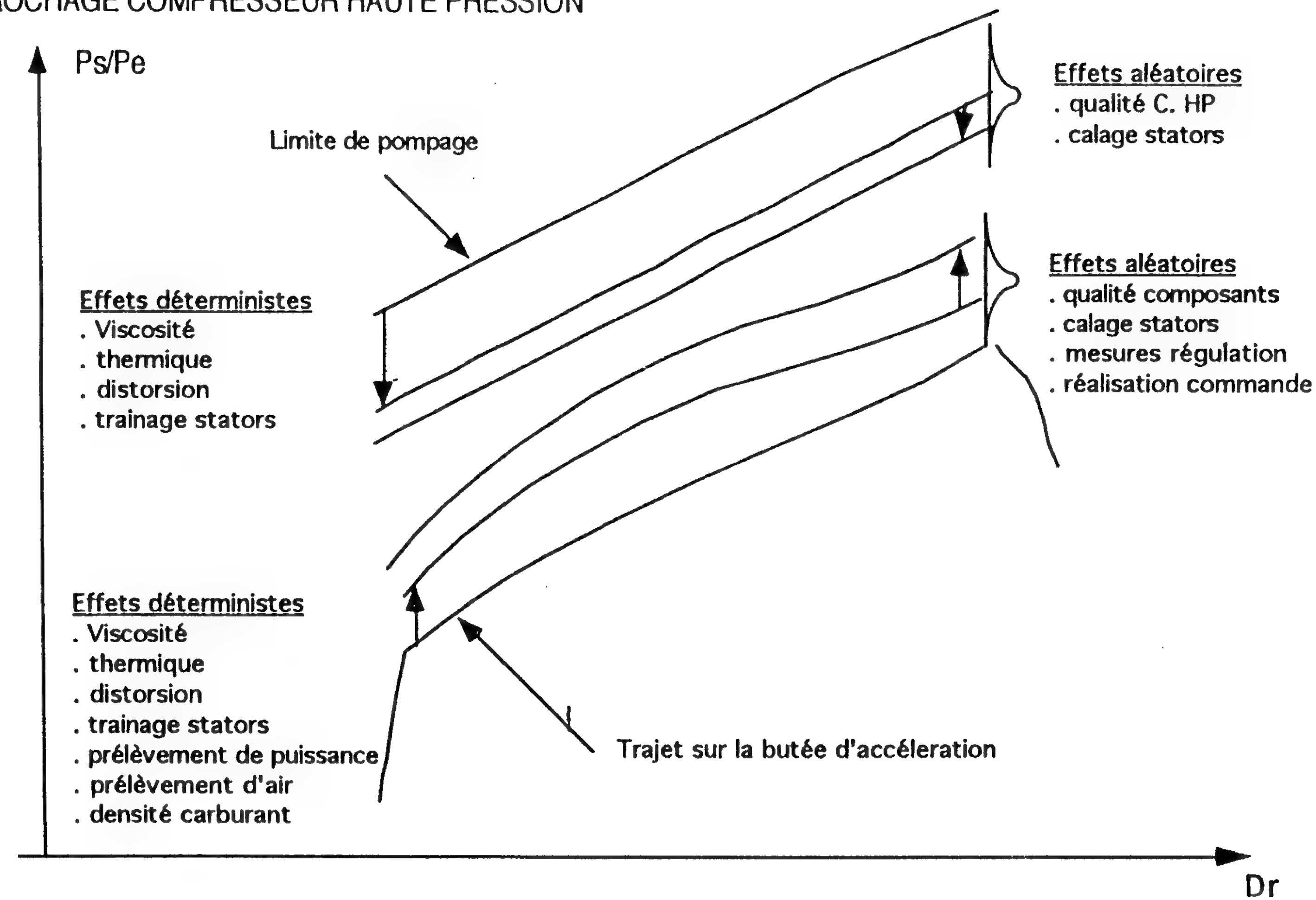
4. CONCLUSION

L'épreuve Bon de Vol (60 vols) s'est terminée le 13 février 1996 et a permis de qualifier le moteur fin mars 1996.

BON DE VOL M 88

DETERMINATION DES DEREGLAGES

DECROCHAGE COMPRESSEUR HAUTE PRESSION

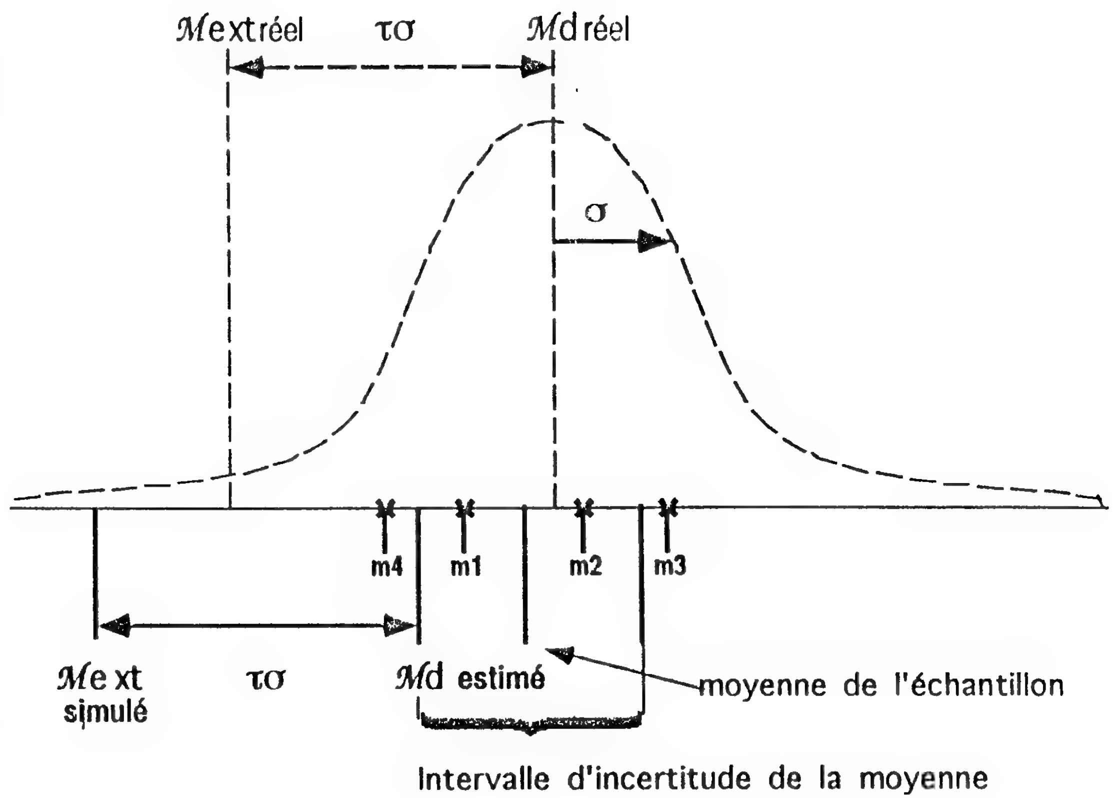


BON DE VOL M 88

DETERMINATION DU MOTEUR MOYEN

RISQUES CLASSES :

- DECROCHAGE COMPRESSEUR H.P.
- DECROCHAGE COMPRESSEUR B.P.
- BLOCAGE DEVISSAGE



Pour obtenir le moteur représentatif du moteur extrême , on dérègle m4 de telle sorte qu'il coincide avec $\mathcal{M}$extsimulé

BON DE VOL M 88

DETERMINATION DU MOTEUR MOYEN

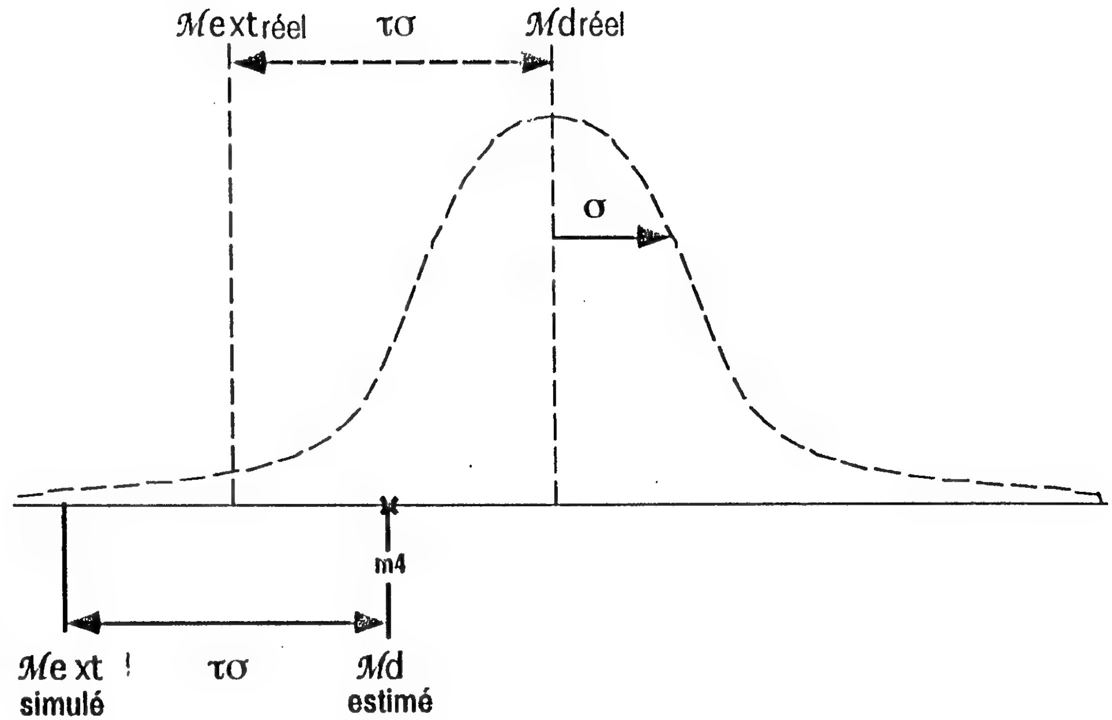
RISQUES TRIES :

- EXTINCTION CHAMBRE
- RALLUMAGE REDEMARRAGE
- EXTINCTION P.C
- NON ALLUMAGE P.C.

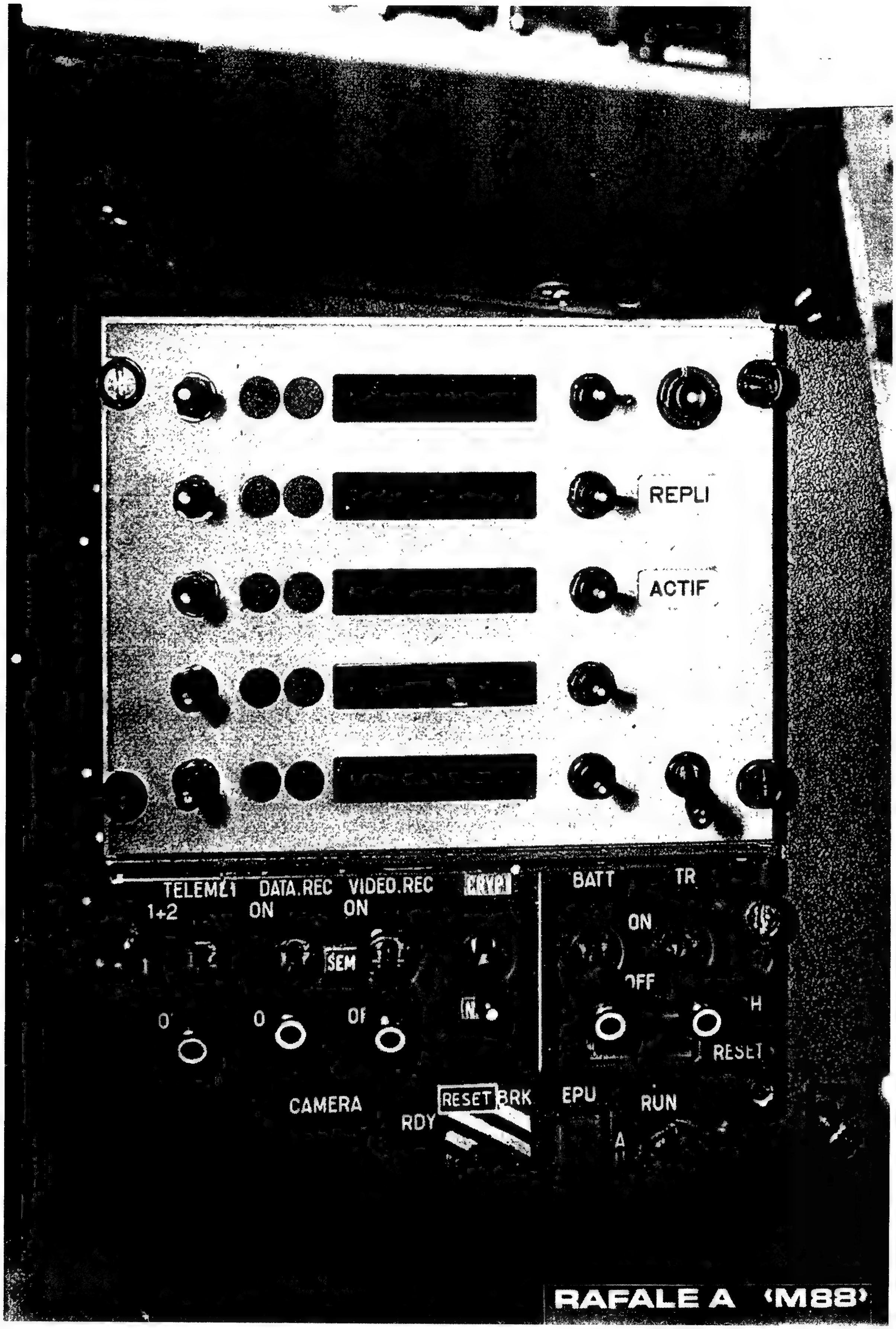
résultat du tri :

m4 < m2 < m1 < m3

m4 =moteur le plus défavorable



Pour obtenir le moteur représentatif du moteur extrême , on dérègle m4 de $\tau\sigma$ telle sorte qu'il coincide avec $\mathcal{M}$ext


REPLI
ACTIF
DATA.REC
ON
VIDEO.REC
ON
SEM
BATT
TR
ON
CAMERA
RESET
BRK
RDY
EPU
RUN
RAFALE A (M88)

SERVICE RELEASE AND "SAFETY CRITICAL" SOFTWARE

Dr K.S.RODGER

Manager Electrical/Electronic Systems

Rotary Wing Aircraft Department

DTEO(Boscombe Down)

SALISBURY

Wiltshire, SP4 0JF, UK

DTEO is a division of DERA an Agency of the Ministry of Defence

INTRODUCTION

As is well known, software is increasingly used to improve operational effectiveness. It is also well known that every innovative use of technology results in a change to the types of hazard and therefore introduces the potential for reduced safety. This paper considers what is required to recommend release of aircraft into service when safety is dependent on the "correct" operation of software. The paper starts with a general description of a release to service and of how it should be derived and continues with a discussion of testing its and rôles, contributions and its limitations. Since software is inevitably associated with electronics the paper next considers how the safety implications of using electronics should be assessed before consideration of how safety critical software should be treated by certifying authorities.

The views expressed in this paper are those of the author and are not necessarily DTEO policy.

RELEASE TO SERVICE

In this paper, the generic term "Release to Service" is used to mean a non-specific authorisation for armed services to operate (i.e. fly, service, maintain, transport) aircraft in peace-time, it is not supposed to reflect the existing practice of any National Authority

The armed forces train in peace-time to prepare for war and although some expansion of the operating envelope is to be expected following a transition to war, too great a change would reduce the value of training and could result in a reduction of war-time effectiveness. Hence, a release should permit training under conditions that, as closely as possible, resemble those pertaining in war, implying a requirement to maximise the certified envelope.

Of the numerous sets of conditions that define a recommended envelope, we shall focus on three: 1. Limitations anticipated from the design, e.g. carriage points limit the weapons that may be carried; 2. Restrictions not anticipated e.g. the airflow under the aircraft may restrict release for stores; and, 3. Restrictions resulting from a lack of evidence, e.g. pertaining to correctness of software. A "perfect" release would contain limitations only.

We now define release to service as: "An official document defining the operating envelope within which the aircraft is simultaneously fit for purpose and safe to operate." Theoretically, it should be written in the sense that, that which is not explicitly permitted is forbidden. However, fundamental considerations (Reference 1), concerning our inability to exclude undecidable elements, make this impossible; some aspects must be left to interpretation, e.g. common sense and airmanship.

Clearly, any release should be based on technically sound recommendations derived from a rigorous analysis of the aircraft and should include a safety assessment. All safety assessments should start from the following axioms: 1. All certifications are predictions; 2. If any item is to be relied on, it must be reliable; 3. If an aircraft is to be certified as safe, it must be demonstrably safe; 4. Some danger is inevitable, which implies that there should be a safety target[1]; 5. Justification that a safety target has been met must be rigorous; and, 6. No component can be more critical that its system. It will be assumed that "Fitness for Purpose" is judged elsewhere

Figure 1 shows the first two levels of a fault tree depicting "Death or Destruction" with an acceptable upper limit for the rate of occurrence of $C_{c.,}$ in which each "contributor", shown as ①② etc. has been ascribed a dis-agregated portion C_1 to C_m where "m" is the number of contributors. There being no limit to the number of ways that a system may be lost, an artificial termination must be made by the analysis on the basis that the contribution from all other sources is suitably small, e.g.. less than some criterion fraction of C and safety is defined by: "Loss rate shall not exceed $10^{-n}\ h^{-1}$", where n is a positive integer.

SAFETY ASSESSMENTS

Although a quantifiable definition of safety is required and the form given here is commonly used and attractive, there are limitations inherent in this definition. The expression implies the use of statistics and their use requires validation.

The mathematics of statistics involves calculations of random processes only and for their application to the real world to be valid, it is necessary that the processes being analysed may be represented as random processes to some known

1 *"Safety target" implies imprecision and that its attainment will be accepted on the basis of human judgement, of which more later.*

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

Top Level Aircraft Loss Model

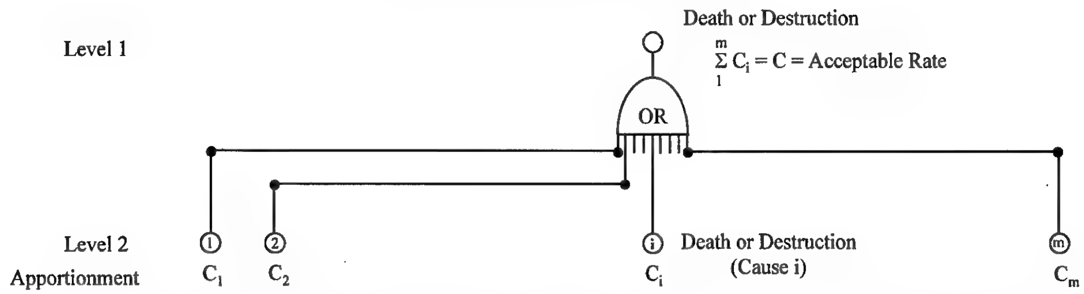


Figure 1 *Shows the first two levels of a fault tree depicting "Loss of Aircraft or Death" with an acceptable upper limit for the rate of occurrence of C in which each "contributor", shown as ①② etc. has been ascribed a dis-agregated portion C_1 to C_m where "m" is the number of contributors. There being no limit to the number of ways that a system may be lost, an artificial termination must be made by the analysis on the basis that the contribution from all other sources is suitably small, e.g.. less than some criterion fraction of C_c.*

level of approximation. However, it is possible that a loss could occur for reasons that are purely deterministic, e.g. due to some unintended feature of the design and contributions from such causes must be dealt with by other means.

Where the use of statistics is valid there is the question of "confidence" in the prediction. The theory of the system being analysed may be used to manipulate empirical data to calculate a loss rate which, it is expected, would not be exceeded in y% ($0 < y < 100$) of cases; the y% confidence level. Unfortunately, this is a recursive problem concerning confidence of confidence etc. with no known solution. However, used for electronics, experience suggests that if a constant rate of occurrence is assumed and the 95% confidence level is used, the answers are not too bad. However, statistics should be used as a last resort only, they are an admission that we do not control or cannot measure what is going on with sufficient accuracy.

SAFETY CASE

Recommendations can only be based on the assessor's own understanding of what the aircraft is, how it works and what it will do when something goes wrong. Generating that understanding is difficult for an external third party and therefore, since February 1992, DTEO(BD) have requested Project Offices to required the aircraft's Design Authority (DA) to supply safety cases. In these cases the DA assesses the impact on safety from the use of electronics and present their reasoned argument why the aircraft is simultaneously fit for purpose and safe to operate.

Starting from the presumption that aircraft are not adequately safe until adequate safety has been rigorously established, the case is reviewed critically by DTEO(BD) and our recommendations (pertaining to the use of electronics) for release to service are derived from our interpretation of that review. The extent of the case and depth of our assessment is determined by the consequences of an error. Thus, some times it may be possible to accept a case consisting of little more than a system description and high level analysis and at other times it may be necessary to analyse some parts of the system in very great detail. The analysis stops when it is shown that, the predicted loss rate, judged against the safety target, is acceptably low and,

$$_1\Sigma^k C_j \ll C_i \qquad (1)$$

where C_j is the credible upper limit of loss rate due to the "unconsidered" element j and k is the total number of such elements, or that the predicted loss rate is unacceptably large, or that the evidence is insufficient to support any conclusion at all. If either of the latter cases pertain, restrictions must be recommended to the release.

SPECIFICATIONS AND STANDARDS

Specifications and standards are irrelevant to making recommendation for release to service. However, they may be made conditionally relevant[2] for components, if relevant constraints can be rigorously established for each application. Specifications and standards are theoretical statements. They are (hopefully) derived from the known laws of science whose correctness must be taken on trust. However, the theory used must be able to derive the rules of elementary arithmetic and Gödel's incompleteness theorem (Reference 1) therefore implies that no specification or standard can be complete. Clearly, meeting an incomplete objective cannot be a sufficient condition.

To be useful, a specification must include statements of the requirements, acceptance criteria and methods of assessment. However, the incompleteness theorem also tells us that theoretical proof of compliance is impossible. Additionally, because of the inevitable presence of error in measurements, empirical proof is also impossible. The argument is similar with respect to standards. Standards are recipes based on experience and, for new items, there can be no proof that a specific standard will be relevant to making recommendations or release to service. If proof that a condition has been met is impossible, that condition cannot

2 *Relevant under defined conditions called constraints below.*

be a necessary condition. If a condition is neither necessary nor sufficient it is irrelevant.

However, if part of a specification or standard is written in a form that, within defined constraints, its relevance is provable, then its satisfaction would be a relevant condition. Later in this paper it is argued that congruence between one abstract item and its abstract descendent is proof that development has introduced no additional danger. This does not imply that use of the item is safe which, of course, requires assessment of the parent item. Gödel's incompleteness theorem implies that at some point in the argument "correctness" has to be accepted as being "obvious". Whereas this is inevitable, this step must not be taken lightly, but only after sober thought and only once the assumptions involved have been defined as clearly as possible and reduced to the simplest form possible.

PROOF

Because there is no known way to either establish completeness of an argument or to eliminate error from measurements, proof is only possible in a restricted sense. It is important to define these limitations as clearly as possible thus enabling the risks they imply to be eliminated, reduced or at least recognised and accepted. Proof (see for example Reference 2 for further discussion) may be defined as: "The rigorous justification of a proposition's correctness within a defined set of assumptions".

Justification should follow the structure of a proof, e.g. as used by Euclid, and should fail only because of inevitable incompleteness and empirical error. In all cases, the argument supporting the justification should start from a system description and contain both a high level argument, giving the main structure of the case, and supporting evidence of sufficient detail to establish the proposition within the confines of the high level argument. The objectives of the justification must be clearly stated and the assumptions clearly identified and justified. All conclusions must be derived by reasoned argument, and clearly stated such that their derivations can be challenged. Finally all of the objectives must be satisfied by the conclusions. In particular, a soundly based recommendation for release to service must include a rigorous justification that software will not add an unacceptable contribution to the aircraft's loss rate. In order to predict that, it is necessary to have an understanding of what software is and how it can affect losses.

SOFTWARE, COMPUTERS AND SAFETY

The IEEE define software as: "Computer programs, procedures and possibly associated documentation and data pertaining to the operation of a computer system.", which establishes that software is associated with computers, that it is described in documents and infers that it is an abstract item. However it does not really help us understand what software is. In order to develop that understanding we need first to know what a computer is and how it works. We shall define a computer as: "Any device used to generate (approximate) solutions to equations.".

As a pure practicality, such solutions must be indirect via some form of control equation, e.g. Newton's method of generating approximate roots. Thus a computer's sole function is to provide an approximate solution to a defined control equation. If we restrict our discussion to digital computers, that solution is achieved by a set of switching operations determined by the programme and past input data. Representing digital computers as finite state machines we may view the programme as the definition of the machine's initial state[3] and we now re-define software as; "The recorded process used to generate the definition of its computer's initial state.".

For the moment, we shall confine consideration to an ideal computer for which practical considerations of computer utilities, e.g. memory capacity, bus loading , do not impose any limit. This computer's behaviour is statically deterministic since, once the set of initial states is determined, its behaviour can be predicted without the need to run a computer, i.e. the computer's trajectory through state space may be predicted for any input stream. Further, if we suitably restrict the set of feasible input data such that it is possible to prove, for any arbitrary combination of those data, that the corresponding states of the computer correspond to an adequately accurate solution, then it has been proved that the software has introduced no additional danger. If this computer's initial state maybe fully and unambiguously determined from the software's requirements, then there would be a rational basis to claim that no restriction is required due to the use of software

Unless special measures are taken, the programme will not necessarily define the states of all switches and some may be set by processes which are not under the control of the software. Clearly, if some of the initial switch positions are not determined, prediction of the computer's behaviour will be impossible even within a restricted envelope of input data. Further more, unless additional steps are taken, there will be no evidence that the initial sates are controlled. In either case, there can be no rational basis for recommending release to service.

Design cannot fail in the sense "go wrong", break or wear-out; it is either right or it is wrong, e.g. the threads of the nut and bolt either match or they do not and that will never change. Design cannot be "maintained", at least not in the sense that hardware can, it can only be modified, Reference 3. Moreover, since design, as opposed to its manifestation, is entirely abstract, it is not amenable to empirical testing and can be tested only by theoretical assessment, itself a theoretical entity. It is always possible however to test the manifestation. (Will the nut "run" on the bolt?) However, because nuts and bolts are so simple we forget how heavily the design of these tests and the analysis of the results rely on our theoretical understanding of nuts and bolts. The real difference is that software is rather complex and, unless we develop understanding we have no basis for defining the tests.

---

3 *In this respect, software is like the design process which generates a working drawing of (say) a nut and bolt. In this model that drawing corresponds to the programme. There is a further analogy in that design is often seen as actually being the working drawing and software as the programme, both are clearly dangerous views.*

TESTING, FAILURE AND DEFECTS

Technical arguments supporting recommendations for release to service must include rigorous/formal justification that no design defect is able to jeopardise attainment of the safety target. For example, because the number of test points in an aircraft's flight envelope is infinite, complete testing (100% coverage) is impossible. The problem is made tractable by the application of the theory of flight, which tells us what that aircraft's approximate behaviour will be. Furthermore, it is the tester's understanding of the theory that indicates where the weak points of the theory are and, therefore, what tests are required. There is no reason to treat software differently, indeed because of its complexity we should be more rigorous in our approach.

The number of test points in a computers envelope of states is finite but so large that 100% testing is sill impossible. For example, in five 16 bit registers there are 2^{80} ,i.e. about 10^{24}, possible combinations of bits. At a rate of $10^{-6}s^{-1}$, 100% test would take about 3 10^{9} years or 20 times the expected lifetime of the sun. However, human babes, consisting of about 5 10^{26} atoms are assembled in about 40 weeks, a child can be taught chess, having a huge number of potential moves, in less than an hour and computer chess games are cheap to buy. These examples suggest how we might develop a theory how software could be developed such that it is verifiable. A child is not taught every chess move but is taught about 25 rules, and a baby is also assembled according to a finite set of rules, used repeatedly. If it can be proved that software has been developed using a few rules, the number of necessary tests will be finite also, approximately equal to the number of rules. Lastly, embryo development imposes rigorous control, especially at the beginning, to ensure adherence with the rules. By analogy, we require software to be developed using a few rigorously imposed rules.

Returning to the role of testing we can now see that testing does not test the object but tests the tester's understanding.

Aircraft Loss Model to Four Levels

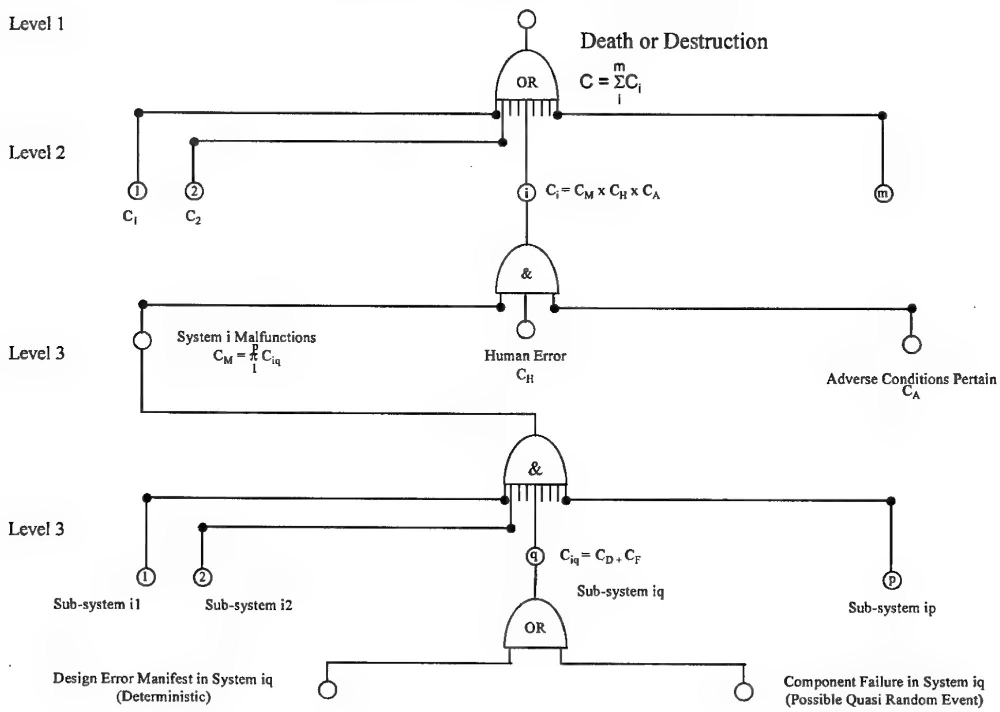


Figure 2. *Shows the first four levels of the fault tree shown in Figure 1. The specified Level 2 event "i" is expanded in a general form of a p-plex (sub-)system of which the "q^{th}" is expanded also in a (near) general form. (The positioning of "Human Error" and "Adverse Conditions Pertain" could be moved or repeated depending on specific circumstances.)*

This paper only addresses software that, if it fails, increases the predicted loss rate above the criterion value. Since software is inevitably associated with electronics, it is necessary to discuss the safety implications of electronics before progressing to discuss the safety implications of software.

Figures 2 to 4 show how such software may be recognised; Figure 2 is quite general and is an extension of Figure 1. It shows that each contributor to "Death or Destruction" must result from the addition of "system malfunction" and "adverse conditions pertain" and (possibly) "human error".

We shall restrict discussion to losses that are initiated by system malfunction[4]. The loss rate will be acceptable only if the rate of malfunction, multiplied by both the conditional probability that adverse conditions pertain and the conditional probability of human error is less than or equal to the budget ascribed to this loss mechanism. However, as Figure 2 shows, the malfunction may occur either because of a component failure or because a design defect becomes manifest. Whereas, under some circumstances, the former's rate of occurrence may be calculated using statistics, the latter's may not.

A Logical Transformation

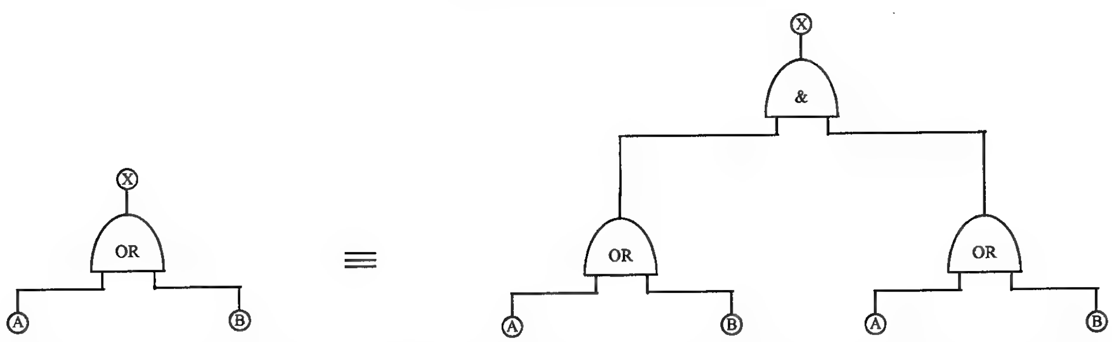


Figure 3. *Shows a simple equivalence of two logical representations.s, the former's rate of occurrence may be calculated using statistics, the latter's may not.*

Loss Model for a Specific Duplex System

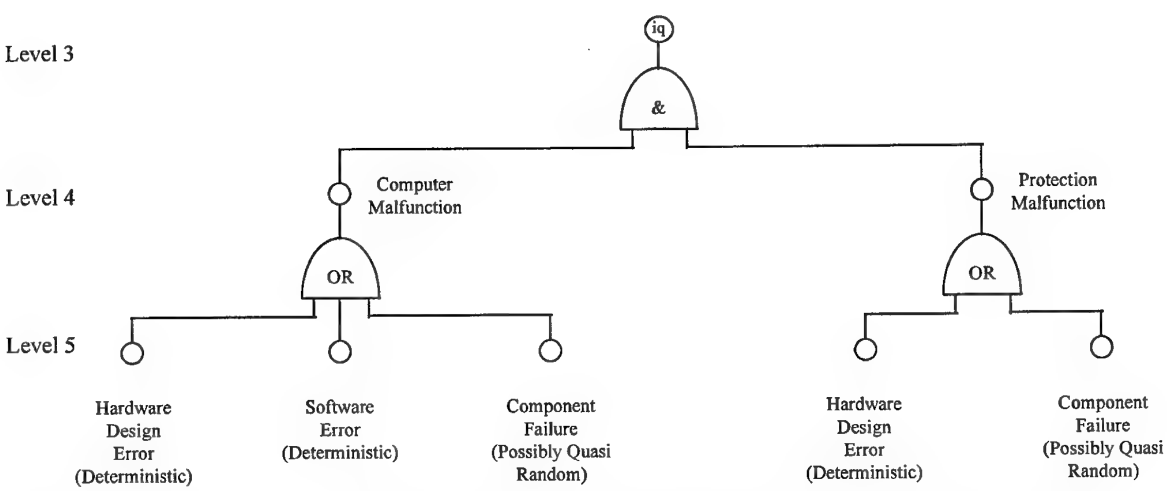


Figure 4. *This analysis of a specific duplex (sub-)system at levels 3 and 4, is derived from Figure 2 using the transformation shown in Figure 3. The redundant structure of logic gates reflects the system's design, it is not a minimised form*

---

4 *Unexpected behaviour.*

Figure 3 shows the basic logic which links the general Figure 2, to the more specific Figure 4. Figure 4 shows a specific duplex system consisting of a computer, its attendant software and some protecting hardware, for which a computer malfunction could cause loss of the aircraft. This loss corresponds to the i^{th} cause of aircraft loss shown in Figures 1 & 2. In this system, simultaneous computer malfunction and a malfunction of the protecting hardware are required to cause a system malfunction. We assume that the rate of random failure may be predicted to tolerable accuracy using statistical methods and that the designs of both the computer and the other hardware are well understood such that no malfunction will occur as a result of their designs. System malfunction now requires either, 1. both a failure of the protection hardware and a software error to become manifest simultaneously or 2. hardware protection and computer hardware to fail simultaneously. We shall assume for this discussion that failure of computer hardware is made suitably improbable (e.g. by duplication)..

Despite continuing research, there is currently no established way to predict the rate of error manifestation. Hence, the analyst must assume the worst, i.e. manifestation occurs with probability one, and compare the hardware failure rate with the budget allowed for the i^{th} system malfunction at level three in Figure 2. If the failure rate is less than or equal to that budget, no manifestation of software error can increase the system's loss rate above its budget[5]. This paper addressees exclusively software in systems that do not meet this criterion[6] for which the analyst now requires proof that no error shall exist, i.e. that no error has been introduced by the software[7].

REQUIREMENTS AND CONSTRAINTS

As we have seen above, the software requirement is to provide adequately accurate solutions to an equation. Since all equations may be written in the form:

$$X = 0 \qquad (2)$$

we may infer that requirement's capture is trivial[8] and does not pose problems for the software engineer. However ,the constraints certainly do.

Constraints will be divided into three groups; "System Imposed", "Customer Imposed" and "Supplier Imposed". The first includes timing and accuracy constraints, i.e. those constraints which, if violated will result in significant loss of control. The second includes e.g. spare capacity (on the data bus or in memory) security, ease of updating, which may restrict the customer's future activities. The last consists of those constraints that flow from any choice made by the software vendor, e.g. a specific choice of microprocessor, plugs and sockets.

SOFTWARE DEVELOPMENT AS METAMORPHOSIS

A model of fully developed software is shown in Figure 5. It shows a definition of the computer's initial state being derived from the input conditions, all of the conditions and nothing but the conditions. It shows combination of the requirement and the constraints through a transformation having constant intellectual content. In this respect, the process is like the metamorphosis of a caterpillar into a butterfly. However, if certification is required, then the chrysalis must be transparent. Of course it is not suggested that software should be developed this way, only that this is how software should be presented to certification authorities. It is also suggested that if this is done, the manufacturer will save money on development by a reduction in test time, time to find faults and reduced need to re-test, Reference 4.

Chrysalis Model for Software.

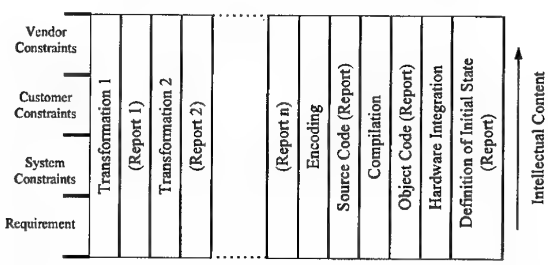


Figure 5 *Development of the object code's installation on the computer should be presented to the certifying authority as a simple process of transformation with no loss or gain of intellectual content, it is not suggested that software should be developed this way.*

If we can now restrict the computer's operating envelope such that its performance is not affected by the capacity of its utilities and its behaviour may be modelled by our "ideal" computer, i.e. it is statically deterministic. This looks like a formidable problem and so it is. However technology suitable to calculate at least some of the limits is discussed in the Annex.

Using this model, the caterpillar represent the requirement and constraints, metamorphosis of the caterpillar represents the transformation of that requirement and those constraints in to the definition of the computer's initial state, which is represented by the butterfly. However, no development is ever fully defined; the metamorphosis of the caterpillar is not fully defined by its DNA, some of the information must be implicit in the laws of chemistry. Similarly, some of the exact definition of how the requirement and constraints will be transformed is implicit in the education of the software designer. Thus we see that development is never perfectly pre-defined, every development necessitates mutation. The certifying authorities are concerned that none shall be

---

5 *Civilian standards, e.g. Reference 5 require all airborne systems using software to meet this criterion.*

6 *Thus, for safety analysis, there are two and only two classes of software; that which maters and that which does not. By extension it can be seen that this is true for any criterion. This conflicts with some very good Standards, such as RTCA/DO 178 A/B and Defence Standard 00-55, which are viewed by the author as being illogical at this point.*

7 *The recorded process used to generate the definition of its computer's initial state*

8 *Writing equation (1) in its explicit form however is not necessarily quite so simple but that is not a software problem. Furthermore, the power of software tempts the designers to use greater sophistication than they otherwise would which often reveals limits to the understanding of system's behaviour.*

malignant mutations which necessitates that those Authorities understand how the software is developed; understanding is the metric relevant to certification.

The chrysalis model shows the need to report software development to the certifying authorities in order to transfer understanding, but any attempt by them to define where in the development the reports must be made would tend to stifle advancement in the processes of software development. However, it may be stated that every stage in the development must be an isomorphic transformation of the preceding stage. Moreover, since the certifying authorities need to understand that the two stages are isomorphic, it is a practical requirement that the transformations are at least prosaic and better that they are technically obvious. By extension of the model to the whole aircraft, wherein software is just one of many visible processes, we see the definition of the computers' initial states as part of the aircraft's detailed design, Figure 6. From this model we can also see that whereas it is feasible for a software developer to ensure that the software introduces no additional danger, proof that use of the computer is safe, partly lies in definition of the requirement and constraints and that lies in the earlier design of the aircraft as a whole.

Chrysalis model for Aircraft Design.

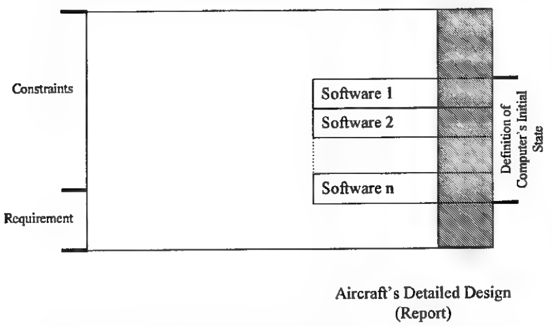


Figure 6. Software is a part of the detailed design of the aircraft.

ENCODING

The activity of encoding is taken as an example of a stage in development. Encodieren ist dem dolmachen endlich. Here, German is used to make point that encoding into (say) Ada is nothing but an act of translation, how prosaic can we be. In fact, encoding is far from prosaic, the mapping between the plain text of the pre-encoded software and the post-encoded (Ada) version is, in general far too complex for their congruency to be agreement by inspection. For that reason, DTEO(BD) rely on the addition of static code analysis[9] using automated tools[10]. There are three reasons for requiring the analysis rather than relying solely on a human reader first, they impose rigor on the analysis, second they ensure completeness and third they leave a retraceable trail of evidence. However, the benefit of static code analysis does not lie in achieving a "pass" rather it lies in the greatly enhanced understanding it imparts to the analysts. Furthermore, if the analysis is conducted by the developer, the time and cost required to reach high quality is reduced References 6 & 7. Of course, static analysis is not suitable for determining every aspect of software behaviour, however recent developments have enhanced its applicability to timing problems Reference 8[11] and detection of "run-time errors", Reference 9, and is also applicable to processes such as assembly and compilation[12].

In fact, every stage of the development, as presented, should look as if it is nothing but translation. Some rules can be proposed to help ensure this happens but, as always, they can be no guarantee. There must also exist a rigorous method of demonstrating traceability. More details are given in the Annex. Lastly it is important to remember that it is possible to write rubbish in any language, including mathematics or, some might say, especially mathematics.

SUMMARY

Starting from a general description of certification for military operations in peace-time and the need for this to be rationally based, the reason for a safety case and the irrelevance of specifications and standards is explained. Following a brief discussion of proof, including fundamental limitations on theoretical and empirical methods, the rôle of software, its nature, relation to digital computers and its potential impact on safety are discussed.

Testing and the significance of failures (potentially a quasi random process), and the manifestation defects (a deterministic process) lead to discussion of the significance of theory in designing validation tests. From a definition of a digital computer as a finite state machine, software is seen to be the recorded transformation of a single requirement and a number of constraints into a detailed description of the computer's initial state. This leads to the definition of two, and only two, types of software; that which could impact a safety target and that which could not. It is pointed out that

---

9 *Not test, static code analysis must not be confused with any form of empirical testing, it is an analysis technique based on the mathematics of set theory and is, in effect, a rigorous form of reading. Once pointed out, any error revealed by static code analysis, syntactic or semantic errors or breaches of discipline, can be seen by a human analysis who is conversant with the languages of the pre-encoded and encoded versions of the software.*

10 *Automated rather than automatic because the tools require intelligent interruption by the analyst.*

11 *The method is extendible to consider overload in computer utilities.*

12 *The IEEE define a compiler as "A computer program that translates programs expressed in a High Order Language into their machine language equivalents." , HOL as "A programming language that requires little knowledge of the computer on which the program will run ---.", Machine Code as "Computer instructions and data definitions expressed in a form that can be recognised by the processing unit of the computer." and an Assembler as "A computer program that translates programs expressed in an assembly language into their machine language equivalents."*

software of the former class must not only be safe but must be demonstrable safe.

Software is put into context as a part of the aircraft's detailed design and it is argued that, whereas safe use of a computer depends on aspects not included in this discussion, e.g. ensuring correctness of the requirement, it is possible to prove that the use of software introduces no additional danger. Finally, encoding is taken as an example activity in the transformation and use of static code analysis in the discharge of its proof conditions is taken as an example of what can be done, this is expanded in the Annex.

ANNEX[13]

For an item to be understood, its behaviour must be predictable to a defined accuracy within defined constraints. If a computers behaviour is to be understood, the resulting source code must be statically deterministic. The language must be unambiguous, which seems to mean in practice that its syntax, static semantics and dynamic semantics must be formally defined. There must exist a method of conducting static code analysis, which must include Data Use Analysis, Control Flow Analysis, Information Flow Analysis, Detection of Run-time Errors, construction of Proof Obligations and Discharge of Proof Obligations which leaves a well defined trail of re-testable evidence. In practice, this necessitates a set of automated tools capable of supporting static code analysis. There must be some means of showing that the essential discipline has been enforced[14].

SUB-SETS

Computer languages are so expressive that no programme ever uses the whole capability of the language. In a well a controlled development, a sub-set is defined to reduce the problems inherent in using large programming teams, as well as to preclude the less "safe" aspects of the entire language. Sub-sets used in safety critical applications are typically the most carefully defined since certain constructs produce code that is un-necessarily difficult to understand. More recently the advantages of formally defined language or sub-sets have been recognised.

DISCIPLINE

Without the enforcement of good discipline the chances of generating demonstrably safe software is very small. Regardless of the language, the encoding standards must include an insistence on a good and recognisable style and the enforcement of discipline. This should include various lists of constructs, e.g. those that are legal within the chosen language but are; 1. Prohibited within the discipline of the chosen sub-set for stated reasons, e.g. result in indeterminate code; 2. Strongly discouraged such that their use is genuinely restricted to those cases where their use is truly necessary; 3. Discouraged in order to maintain a good house style.

The last of these is included because software written using the minimum set of constructs is easier to understand and therefore less liable to error both in its writing and in its analysis.

ENFORCEMENT OF APPROPRIATE SUB-SET(S)

Having selected a sub-set, it is necessary to ensure that its rules are not broken, otherwise the assumption used in conducting the analysis may be invalid. Although evidence of violations cannot be suppressed, it can be hidden by nefarious programming and it is unreasonable to expect these to be identified by human scrutiny unless tools support is used to detect, mark and record violations. In addition, if they are rigorously or better formally defined, the tools also define the necessary conditions for an analysable sub-set.

TRACEABILITY

Clearly requirements must be traceable through the process of encoding. The tools must produce reports which reveal weaknesses in the means of relating source code to pre-encoded specification.

CONTROL FLOW ANALYSIS

This analysis identifies and analyses the possible paths through the source code. The tools must identify or preclude use of unsatisfactory control structures and redundant code. They must also identify lack of structure in programming, e.g. multiple entry and/or exit points, obscurities caused by poor loop structure, jumps into loops, mixing of programme and data statements and imprecisely defined structure. It helps the analyst discover poor decomposition and/or commenting and obscurely named variables; ambiguously named variables are identified.

DATA USE ANALYSIS

This analyses the sequence in which the variables are written to and read from. The tools must identify cases where variables are used before being set or set and not used. These anomalies may not be errors but may be examples of programming styles, however they must be identified and justified as they may become malignant mutations after modification.

INFORMATION FLOW ANALYSIS

Identifies the dependencies between input and output, the tools must identify these dependencies enabling the analyst to discover unwanted, unexpected or missing dependencies.

CONSTRUCTION OF PROOF OBLIGATIONS

These are the logical conditions that must be satisfied if congruency is to be proved between the pre- and post-encoded specifications, this can be a difficult problem, especially if the function is spread between more than one module. The tools must be capable of producing the path functions from the code and verification conditions from the specification.

DISCHARGE OF PROOF OBLIGATIONS

The tools must support both formal and rigorous discharge of proof obligations. A formal proof is a strictly well-formed sequence of logical formulae such that each one is derived from formulae appearing earlier in the sequence or as instances of axioms of the logical theory. It proceeds by simple matching of syntactic structures and as such is strongly dependent upon the form of syntactic categories

---

13 *Uses numerous sources especially Defence Standard 00-55.*

14 *MALPAS ™, SPADE ™ and SPARK (with verification condition generator) are known to meet these criteria. for further information see References 10,11 and 12.*

such as formulae and terms. Rigorous argument may be viewed as a mathematically complete description of how a formal proof might be made, such that it can be converted to formal proof without additional information[15]. Whilst not providing the level of confidence achievable from formal proof, it has been accepted in the past but the effort required from the assessors is very great.

RUN-TIME ERROR

The analysis tools must detect run-time errors, having a dedicated tool to find these errors reduces the time and cost of path analysis.

UTILITIES

A rigorous (or formal) method justification that the computer's utilities, e.g. memory, bus loads, will be adequate for the task is required.

REFERENCES

1 Gödel "Uber Formal unentscheidbare Sätze der *principia Mathematica* und Verandter Systeme, I." Monatshefter für Mathematik und Physic, 38 (1931) pp 173 - 198.

— "On Formally Undecidible Propositions" New York, Basic Books 1962 (A translation of Gödel's paper and some discussion.)

Encyclopædia Britannica 15th Micropædia IV page 549

2 Encyclopædia Britannica 15th Micropædia VIII page 238

3 D.Hawkes "Software in Safety Critical Systems: the Certification Challenge" Flight Safety Conference Amsterdam 1994.

4 M.Coxford and J.Sutton "Breaking Through the V&V Bottleneck" Ada in Europe 95 Conference Frankfurt October 1995.

5 JAR/FAR 25.1309

6 M.Sutton and B.Carré "Achieving High Integrity at Low Cost; A Constructive Approach" Avionics Conference Heathrow 1995

7 M.Sutton and B.Carré "Ada: The Cheapest Way to Build a Line of Business" Tri Ada 95 Anaheim USA

8 J.Garnsworthy, I.O'Neill and B.Carré "Automatic Proof of the Absence of Run-time errors" Ada UK Conference London 12 - 14 October 1993

9 A.Burns, R.Chapman, A.Wellings "Combining Static Worst-case Timing Analysis and Program Proof" Real Time Syst. J

10 MALPAS™ is a trade mark of TA Constancy Services Ltd, The Barbican, East Street, Farnham, Surrey GU9 7TB, UK.

11 SPADE™ is a trade make of Praxis plc, 20 Manvers Street, Bath, BA1 1PX, UK. The SPARK Examiner is a version of SPADE designed for use with the SPARK sub-set of Ada.

12 B.Carré, Chapter 8 "Programme Analysis and Verification" in "High Integrity Software" edited by C.Sennet, Pittman (1991)

13 J.Barns "High Integrity Ada - The SPARK Approach" (To be published) Addison Wesley 1997

Any views expressed are those of the author and do not necessarily represent those of the Department/HM Government.

15 *Among other things, the analysis must identify those part of the pre- and post-encoded specification that are to be compared. Formal proof requires a (sufficient) rigorous argument as a first step. In addition to providing the basis for the formal proof this will also provide insight into the reasons for the program being correct.*

C-17 Enhancements to a Flight Test Planning Program

Cheryl Canody
Tybrin Corporation
307 E. Popson Ave, Rm. 415
Edwards AFB CA 93524
Tel (805) 275-4579
Fax (805) 277-6054

Marle D. Hewett
G&C Systems, Inc.
30210 Rancho Viejo Rd, Suite D
San Juan Capistrano, CA 92675
Tel (714) 248-7212
Fax (714) 248-5237

Summary

This paper presents the enhancements incorporated into TEST_PLAN, a commercially available flight test planning program, for the C-17 follow-on test program. TEST_PLAN is a software package for UNIX and VMS based workstation computers that allows flight test engineers (FTE's) to plan and track flight test programs by mapping requirements to test points, flights, and flight test maneuvers.

TEST_PLAN is integrated with the Oracle relational database management system (RDBMS). Test points and requirements are stored in Oracle tables. The software provides automated tools that allows FTE's to query these tables to obtain lists of test points that can be assigned to maneuvers and flights to construct a flight test plan.

The 417th Flight Test Squadron (FLTS) at the Air Force Flight Test Center (AFFTC), Edwards Air Force Base (AFB), funded four major enhancements to TEST_PLAN to support the C-17 follow-on flight test program. These enhancements are:

1. incorporation of the C-17 Test Parameter Requirements (TPR) database into TEST_PLAN;

2. implementation of an Instrumentation Discrepancy Report in TEST_PLAN;

3. integration of FrameMaker with TEST_PLAN to implement an automated flight test card generation facility; and

4. instituting a requirements compatibility matrix using Oracle tables and compatibility definitions provided by the administrator.

The details of these enhancements are presented in this paper.

C-17 Test Parameter Requirements (TPR) database

Each test point has an associated list of instrumentation parameters, a TPR, that are needed for data collection and postflight processing. In TEST_PLAN, the TPR that will provide the necessary data is included in the test point definition when the test point is created. As the FTE plans a mission and assigns the test points within TEST_PLAN, the instrumentation engineer can perform an instrumentation check that will compile a list of all the parameters needed for the mission and check them against the aircraft instrumentation parameters. A system of color coded flags are used to alert the instrumentation engineer of any potential problems with the instrumentation in advance of the mission, allowing for issues to be addressed and remedied.

In addition to the TPR's that are assigned to test points, the instrumentation engineer has the capability to assign TPR's to the mission. This allows the instrumentation engineer to make sure that instrumentation that is necessary for all missions regardless of what the testing is, or for all missions for a certain discipline, is taken into account when the

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

aircraft instrumentation is setup. Examples of this are safety-of-flight parameters for all missions or the parameters required for airdrop missions only.

All the TPR information is stored in a system of 37 Oracle tables, referred to as the Test Parameter DataBase (TPDB), that contain information such as the instrumentation measurand name, title, applicable software revision, bit configurations, calibration information, and special requirements. TEST_PLAN uses 6 of these tables to gather the TPR information related to each aircraft being tested. For the lists of measurands, the tables contain information such as the TPR name or number, applicable software revisions, list of measurands that make up the TPR, and the applicable aircraft. TPDB allows the number of unique TPR lists to grow as the aircraft is modified, where a TPR's uniqueness is based on either a software configuration update/change, discrete parameter bit changes, aircraft effectivity, or measurand bus location changes. The physical size of TPDB is limited only by the amount of storage space available on the system hosting the data and how much of it is allocated to TPDB.

The TPR data is entered by the responsible project engineer(s) after they have determined if there are any changes to existing measurands or TPRs or if there will be any new instrumentation added to the aircraft that must be defined. New instrumentation can be added to an existing TPR or a new TPR can be created. The project engineer coordinates with the aircraft instrumentation personnel on the accuracy of the information as well as to inform them of any new or changing requirements. After a TPR is created, the project engineer assigns it to a test point. At this point, the instrumentation engineer may perform an instrumentation check from within TEST_PLAN to verify the aircraft configuration will meet the desired testing requirements.

Prior to this capability becoming available from within TEST_PLAN, the instrumentation engineer was running printouts from the contractors TPDB system and manually verifying that the aircraft configuration would support the desired testing. The time required for instrumentation configuration verification has gone from days to hours, a significant saving in man hours, and has resulted in more accurate configuration checkouts.

Instrumentation Discrepancy Report

As part of the TPR process, a report was needed to assist the instrumentation personnel in properly preparing the aircraft for a mission. After the TPR interface with TEST_PLAN was created, the capability to print the results of the instrumentation check was added. An FTE or instrumentation engineer can run an instrumentation check of the TPRs needed for the mission against the current configuration of the aircraft. Then they can then print an Instrumentation Discrepancy Report (IDR) that lists which parameters are unavailable and for what reason or print the entire list of parameters needed for a mission. Figure 1 shows a sample IDR.

To do the IDR, TEST_PLAN uses an additional Oracle table where instrumentation deficiencies are recorded and tracked through a component of TPDB called Report of Unsatisfactory or Defective Instrumentation (RUDI). Instrumentation that is broken or malfunctioning is entered into the RUDI tables. When it is repaired the entry is closed with a description of the fix. When the Instrumentation Discrepancy Report is run by the instrumentation engineer, TEST_PLAN checks the measurands in the TPR against the RUDI table and annotates any that are listed there. This gives the instrumentation engineer advance notice of measurands that may hold up the testing if the measurands' malfunction is not repaired.

TEST_PLAN creates the IDR by pulling the necessary TPR information from the TPDB tables based on the TPR's specified in the flight plan. First, a list of the measurands/parameters necessary to support the test points is created. This list is then compared to an ASCII file that contains the current aircraft configuration with regard to what parameters are available on the aircraft, what sample rate the parameter is available at, what post flight data stream the parameter will be available on, and what telemetry stream, if any, the parameter will be on. When all the parameters in the TEST_PLAN generated list and the ASCII file have been reconciled, TEST_PLAN then checks the parameters against the data in the RUDI table to verify whether the parameter is functioning or not. All this information is then compiled and presented in the IDR with potential problems flagged.

From this report, the instrumentation engineer can start resolving issues so particular test points can be flown, coordinating his/her efforts with the discipline engineer who will need the data.

Since the incorporation of this feature, the time used to obtain these reports has gone from an average of 1 to 2 hours to a matter of minutes. This allows the instrumentation personnel to get to work on the problems indicated in the IDR sooner and run additional IDR's quickly as the aircraft configuration changes due to repairs, installation of additional equipment, or changes to the test points planned for the mission. The time that was spent waiting on reports is now spent getting the aircraft ready sooner, allowing for a faster turn around of the aircraft between missions. Since the discipline engineers also have the capability to run IDR's, they can stay abreast of the aircraft instrumentation setup and not get caught unprepared for a mission.

Previously, this process was performed on the contractors TPDB system by running several different Oracle SQL scripts, printing the results, and manually verifying problems. This could take several hours to get the printouts and identify the instrumentation discrepancies. With the IDR capability provided by TEST_PLAN, the instrumentation engineer has the results in as little as five (5) minutes to as much as thirty (30) minutes, a considerable saving of man hours. The IDR is also more accurate than the previous partially manual method, increasing flight safety - always a desired result.

Automated Flight Card Generation Facility

TEST_PLAN presents flight plans as a sequence of flight test maneuvers with test points assigned to these maneuvers. It is possible to automatically generate a deck of flight cards from this sequence. In the standard commercial version, TEST_PLAN generates these cards using imbedded postscript code with fixed formats that cannot be changed by the FTE. This automatic flight card generation facility has the potential of generating considerable savings in person hours in a flight test program. These savings are realized at a time when FTE's are usually working overtime to generate flight card decks for the test program. The time savings translates to a general improvement in flight safety during the test program because the FTE's have more time to think about flight plans instead of spending time generating cards using a word processor or a form generation software package.

Even though an imbedded flight card generation facility was available in TEST_PLAN, it was tailored to the knee board cards used by fighters and did not lend itself well to the 8 1/2 x 11 format used by the C-17. The enhancements funded by the 417th FLTS for the C-17 program provided for the integration of FrameMaker, a commercially available document generation and management package, with TEST_PLAN. This integration allowed for the generation and use of a large number of flight card formats generated by a local TEST_PLAN administrator in FrameMaker. This capability was used to provide all the existing templates in use and add additional ones as desired.

To generate a flight card deck, FTE's enter and save flight card data by test point in an Oracle table. The flight card database table is a separate table from the test point table, to which the FTE's have read-only privileges. The FTE's have read and write privileges to the flight card table. The FTE then plans a flight in TEST_PLAN by assigning test points to a sequence of flight test maneuvers. At any point during the planning process, the FTE may generate a deck of flight cards by selecting an appropriate menu item with the flight highlighted in TEST_PLAN. TEST_PLAN creates a FrameMaker file in a data interchange format and starts FrameMaker automatically for the user the first time a card deck is built during a planning session. FrameMaker comes up with the appropriate cover page displayed followed by the flight cards as sequenced in the flight. At that point the FTE is free to modify the cards as necessary in FrameMaker and print the deck. As long as the FTE does not quit FrameMaker, it will be available for viewing any other cards that are created or worked on during the session. TEST_PLAN stays aware of whether FrameMaker is running or not and if it is still running will notify the user of such, instructing them on what file to open for viewing. If FrameMaker has been exited, TEST_PLAN will restart it, opening the card file being worked on automatically.

In addition to test points that may be associated with a particular type of maneuver, TEST_PLAN also allows the FTE to assign up to 25 test points to the

actual flight block itself. This provides the FTE with the flexibility to include points that may apply for the whole mission or maybe even a portion of a mission without having to try and associate it with a particular maneuver at a particular point in the flight. When all points have been assigned to the flight, either in the flight block or the maneuvers, the FTE may generate the deck for the flight. When doing this, the points assigned to the flight block are first in the deck followed by the points in the maneuvers in the order they were assigned. Each deck is preceded by one or more cover pages that list the test points in the order they are assigned to the mission. Figure 2 presents a typical C-17 flight deck cover page. There are currently four standard cover pages - Ground, Low hazard, Medium hazard, and High hazard. TEST_PLAN determines which cover page to use based on the test points defined hazard levels. Whatever the highest hazard level is in the flight plan is the cover page TEST_PLAN will use. For example, a mission may have 23 Low hazard points, 2 Ground points, and 1 Medium hazard test point. Even though there is only one Medium point, that is the cover page that will be used so as to reflect the highest hazard condition of the mission. By looking at the cover page, one can see what hazard level the points are and see which point(s) make the mission that hazard level.

The integrated package provides the FTE with a time saving device that frees him/her to spend more time in planning and less time in flight card creation. TEST_PLAN also allows an FTE to reuse previously planned missions using cut and paste functions, saving the FTE more time in setting up missions and assigning test points. After completing the changes to a mission plan that the FTE is reusing, the flight deck for the new mission can be created and printed. This is an often used feature for regression testing or for build-up testing where the general mission plan is either the same or very similar to an existing plan. Figure 3 presents a typical C-17 flight test card for a test point.

Requirements Compatibility Matrix

When planning a mission, the FTE must also take into account the aircraft system and support requirements needed to accomplish all desired testing. This often requires consultation with the cognizant engineers to ascertain what support is needed from what organizations and whether the requirements are compatible with each other. Some are obvious - a dry runway requirement and a wet day requirement are incompatible, but others are not so obvious. TEST_PLAN allows users to define ten categories of system configurations, eight categories of support requirements, and a loads configuration category. A typical set of systems configurations might be: flight controls, communications, hydraulics, weapons, navigation, and pneumatic. A typical set of support requirement categories might be: weather, operating area, air support, and ground support. In each system and support category, an FTE can build lists of requirements; each list being composed of items stored in an Oracle table. This table contains all systems and support items in all categories and each item's compatibility (or incompatibility) with all other items in the same category. Once each item is defined, it can be combined into lists with other items in the same category. These lists can then be selected and assigned as part of the test point definition process to indicate what support is required for the point to be accomplished. Figure 4 illustrates a typical compatibility list with compatible items indicated by highlighting.

After the requirements' information has been assigned to the test point, the FTE will get an automatic indication of a conflict of requirements, via color coded flags, when points are assigned to a mission within TEST_PLAN. Then, using the Requirements/Limit violations display available in TEST_PLAN, the FTE can see what the conflict is and make a decision on what point to remove, based on testing priorities, to resolve the conflict. Figure 5 illustrates the Planning Display with test points assigned that have load, systems, and supports requirements incompatibilities. The LOAD, SYSTEMS, and SUPPORTS requirements flags are set to indicate the compatibility problems to the FTE.

The Requirements Compatibility Matrix removes the guess work in determining what support items are needed and their compatibility with each other for the FTE, enabling the FTE to plan missions devoid of conflicts. This feature results in time savings for the FTE in planning the mission and for the cognizant engineer by removing the need of coordinating with the FTE to ensure requirements are met. It also allows for an FTE that may not be intimately familiar

with a discipline to plan missions competently, safely, and quickly without having to spend the time to come up to speed on the discipline or having the engineer spend a larger amount of time assisting in the planning of the mission.

Conclusion

In an effort to enhance the quality of flight testing and enable a smaller force to perform the testing, the 417th FLTS invested in TEST_PLAN to provide automated tools for FTE's to construct efficient, safe, and reusable flight test plans in less time. In addition to the generic features available in the software, the 417th also invested in customization work that automated and standardized tasks that were previously done manually or with limited automation. This investment has already begun to reap benefits in reduced man hours to perform these tasks and further benefits are expected as users become more familiar with the system.

TEST_PLAN Instrumentation Discrepancies

AIRCRAFT: T1 - #87-0025 / DATE: 17-AUG-95
PLAN: TEST
BLOCK: B1 / FLIGHT: F1

					TPR	SYSTEM SPS (ACTUAL)				REQUIREMENT/DISCREPANCIES								
										TM			P/F			BOTH		
						1	2	3	4									
Param #	PRI	Title Line 1	Title Line 2	TPR #	STAT	P	P	T/P	P	MSNG	INOP	SPS	MSNG	INOP	SPS	RUDI	SQWK	S/W C
29G303	2	LDGGR CNTRL	SUP3 STATIC	SUBSYSTEM HEALTH	A								•		25			
29G312	2	LDGGR CNTRL	RTN3 STATIC	SUBSYSTEM HEALTH	A								•		25			
314121	2	LCL AOA VANE	UPR 1L CALIB	1700-01	A					•		25	•		25			
314122	2	LCL AOA VANE	LWR 6R CALIB	1700-01	A					•		25	•		25			
314221	2	LCL AOA VANE	UPR 2R CALIB	1700-01	A					•		25	•		25			
903000	1	ALPHA	NOSE BOOM	1700-01	A					•		50	•		50			
905004	1	PILOTSSEAT'	LONG	1700-01	A			25				50			50			
905004	1	PILOTSSEAT'	LONG	2201-AV-ALL	A			25				50			50			
905004	1	PILOTSSEAT'	LONG	2201-01-000	A			25				50			50			
RESD01	2	OVERSPD LIM	CAS	2201-01-000	A		25											•
RESD02	2	OVERSPD LIM	MACH NO.	2201-01-000	A		25											•
RFSD01	2	OVERSPD LIM	CAS	2201-01-000	A		25											•
RFSD02	2	OVERSPD LIM	MACH NO.	2201-01-000	A		25											•
TACM0P	1	PITCH STICK	POSITION-CAL	1700-01	A						•	25	•		25			
TBC70B	2	HORIZ STAB	POSITION	1700-01	A								•		6			
TCCF06	2	ROLL STICK	POSITION-LCL	1700-01	A								•		12			
TDCF06	2	ROLL STICK	POSITION-LCL	1700-01	A								•		12			
UACR00	2	LIB FLAP VALV	SOLENOID CMDS	1700-01	A				200	•		25						
UACR10	2	LOB FLAP VALV	SOLENOID CMDS	1700-01	A				200	•		25						

Page 1

Figure 1

LOW LOW LOW LOW LOW LOW

MODEL C-17A AFS NO. 87-0025, ACFT T-1

PG 1 of ____

MISSION NO. ____________ DATE: ____________
MISSION: ____________________________

TEST COORD: ____________
418 FLTS CC: ____________

PILOT ____________________
COPILOT ____________________
FTE ____________________
LOADMASTER ____________________
ADDITIONAL ____________________

TOGW ____________________
TOCG ____________________
FUEL ____________________
ZFW/CG ____________________

AIRCRAFT LOG TIME		
	HR	MIN
LANDING TIME		
TAKEOFF TIME		
ELAPSED TIME		
	HR	1/10
LOG TIME		
PRIOR TIME		
TOTAL LOG TIME		

SIGNIFICANT CONFIGURATION CHANGES

C-17 RADIO MU = ________
OPS NO.: ____________
CHASE: ____________
TANKER: ____________
MSN FREQs: ____________

CARD LTR	ALTITUDE	AIR-SPEED	TEST	TIS NO.	TEST NO.	HAZ LVL
	----	----	COMMENTS, CONFIGURATION and LOGS	----	----	-
B	FIELD	STAT	SYSTEM INITIALIZATION - MISSION INITIALIZE PAGE. MC 3.1.2	F3462-10	411.001	L
C	OPT	ASREQ	MC 3.1.2 LNAV CAPTURE, AUTOPILOT REGRESSION	F3462-10	431.001	L
D	OPT	340	MC 3.1.2 LNAV TRACK GUIDANCE, AUTOPILOT (REGRES-SION)	F3462-10	431.002	L
E	8,000	250	VNAV - CLB, FIXED EPR & CONSTANT CAS/MACH (REGRESSION)	F3462-10	441.001	L
F	<15000	310	VNAV CLIMB : ALTITUDE CAPTURE (REGRESSION)	F3462-10	441.003	L
G	OPT	310	VNAV - CLB, FIXED EPR - TECH ORDER CLIMB (REGRES-SION)	F3462-10	441.002	L
H	OPT	310	VNAV - CLB, FIXED EPR - TECH ORDER CLIMB (REGRES-SION)	F3462-10	441.002	L
I	OPT	310	VNAV - CLB, FIXED EPR - TECH ORDER CLIMB (REGRES-SION)	F3462-10	441.002	L
J	FL310	LRC	MC 3.1.2 LNAV LEG CHANGE GUIDANCE, AUTOPILOT (REGRESSION)	F3462-10	431.003	L
K	FL310	LRC	MC 3.1.2 VNAV PATH DESCENT w/ AFCP LEVEL OFF	F3462-10	441.004	L
L	OPT	OPT	MC 3.1.2 LNAV DIRECT-TO A NON-ACTIVE A/R ALTERNATE	F3462-10	431.005	L
M	OPT	OPT	MC 3.1.2 RENDEZVOUS, POINT PARALLEL, A/P, ATS	F3462-10	451.001	L
N	1500R	250	MC 3.1.2 AIRDROP, LVAD (REAL OR SIMULATED) A/P ATS	F3462-10	461.001	L

Figure 2

TEST: MC 3.1.2 LNAV TRACK GUIDANCE, AUTOPILOT (REGRESSION) **CARD: D**

TIS NO. F3462-10 . RISK LEVEL: L FLT NO.
TEST. NO. 431.002 C-17A T1

TEST PURPOSE: Demonstrate that the autopilot MC LNAV tracking of the the desired flight plan leg is satisfactory.

INITIAL CONDITIONS	AFCS CONFIGURATION			CONFIGURATION	
ALTITUDE: OPT	ATS : ON		AP : ON	NORMAL FOR CRZ WITH/EXCEPT:	
AIRSPEED: 340	F/D : ON		ID : PILOT	MFD#1	: MAP
THRUST: TFLF	ROLL : NORM		NAV : MSN		:
FLAP SLAT INDX: UP RET OPT	BANK : NORM		EPR : MCT		:
GEAR: UP	THRUST	PITCH	ROLL	DATA: 100	: VIDEO: OPT
WEIGHT: OPT	IAS 340	ALT HOLD	MSN		:
C.G.: OPT					:

PROCEDURE 1) Establish the aircraft in a MC LNAV mode on the desired track.

2) Record the winds aloft on the NAV display.

3) Verify that the LNAV performance during tracking of the desired lateral leg is satisfactory and is not affected by winds and atmospheric upsets.

4) Continue testpoint to collect 1 min of track guidance data.

TIME			
HR	MIN	SEC	
			RECORDS ON
			WINDS:
			ALTITUDE:

Cog. Eng.________

Figure 3

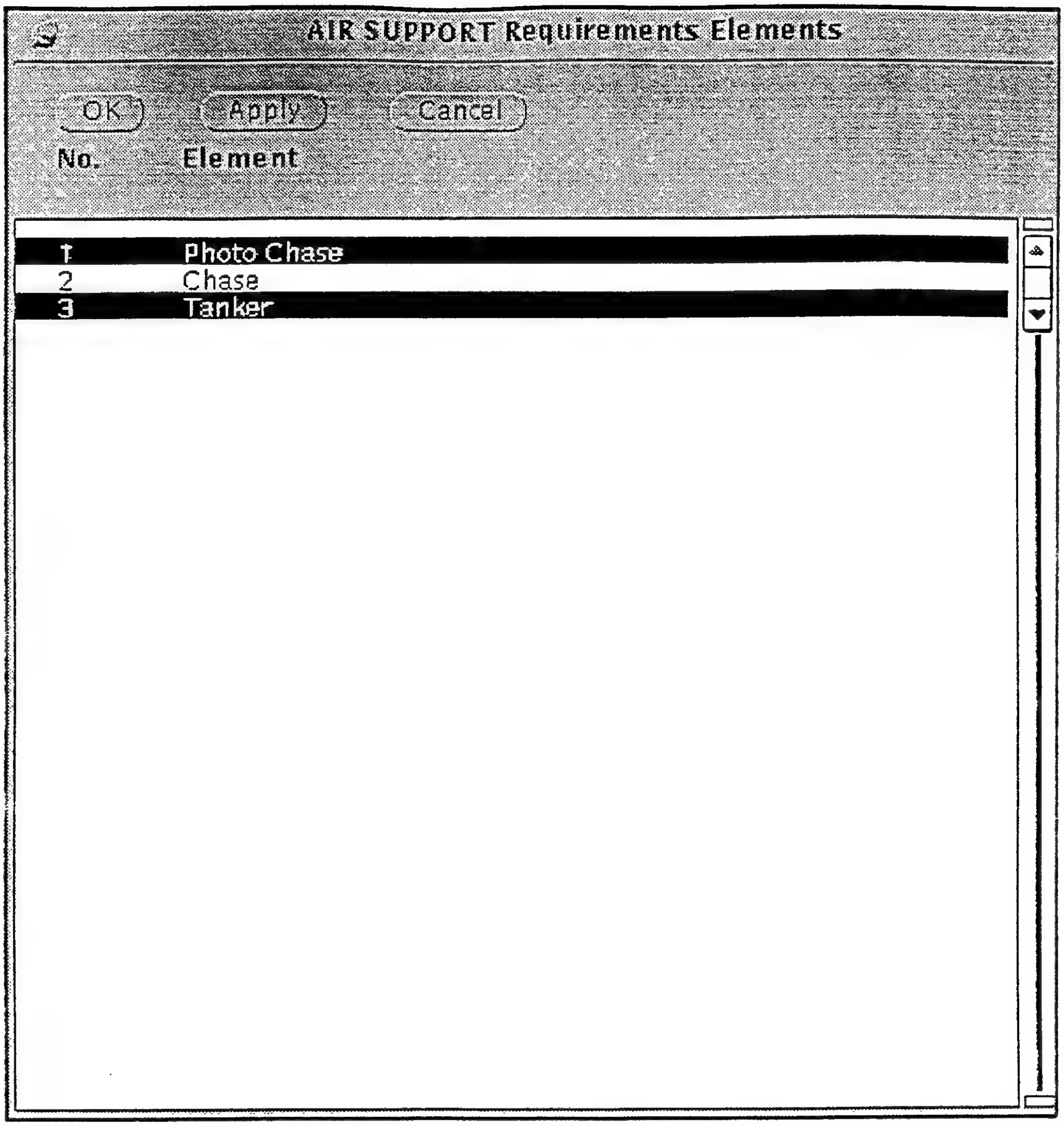
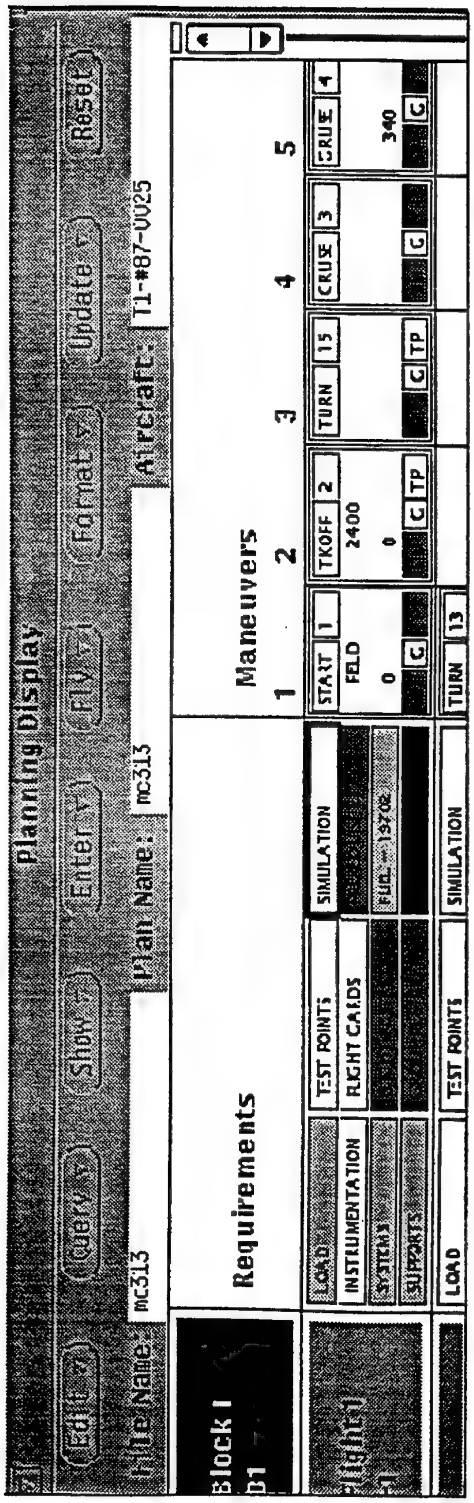

AIR SUPPORT Requirements Elements
OK
Apply
Cancel
No.
Element
1 Photo Chase
2 Chase
3 Tanker

Figure 4


Planning Display
Edit
Query
Show
Enter
Fly
Format
Update
Reset
File Name:
mc313
Plan Name:
mc313
Aircraft:
Block I
Requirements
Maneuvers
LOAD
TEST POINTS
SIMULATION
INSTRUMENTATION
FLIGHT CARDS
SYSTEMS
SUPPORTS
START
FIELD
TKOFF
2400
TURN
CRUISE
340

Reduction of Aircrew Workload Through the Use of INS/GPS While Employing Standoff Weapons

Captain Earl W. Stolz, USAF
Captain Keith J. Kosan, USAF
40th Flight Test Squadron/DOOB
505 W Choctawhatchee Ave Ste 1
Eglin AFB FL 32542-5722
USA

SUMMARY

Modern fighter aircraft are capable of unprecedented attack accuracy. However, the risk associated with close-in delivery against well-defended targets is often high. As a result, current tactics call for delivery of precision-guided munitions from increased standoff ranges. The AGM-130 was designed to fill this need.

The AGM-130 evolved from the GBU-15 family of glide bombs and is equipped with a rocket motor to increase standoff range. With the increase in launch ranges came an increased workload due to difficulty locating targets within the seeker's field of view (FOV). A launch heading offset or crosswind could require the weapon systems officer (WSO) to scan a large area to locate both the target itself and any required waypoints. The midcourse guidance (MCG) program is an enhancement designed to address this difficulty by decreasing workload with an autonomous guidance capability in the midcourse portion of the flight and the ability to point the seeker at the target.

The objective of the AGM-130 MCG test program is to evaluate the benefits associated with reduction of aircrew workload with the introduction of an inertial navigation system (INS) that is position- and velocity-aided by the global positioning system (GPS). This paper will discuss flight test techniques and results obtained from the Phase I test program, which focused on initial integration efforts using profiles to attack vertical targets. Phase II will address the capability to attack horizontal targets and is currently being tested. A secondary objective of demonstrating the advantages of guidance using wide area GPS enhancement (WAGE) corrections was also accomplished.

Testing involved a series of ground functional tests, captive carries in which the aircraft flew the weapon's profile, and three live launches.

The stated goal of the MCG program is to ensure that the target appears in the seeker's wide FOV at 15 seconds time-to-go 95% of the time. In all cases this criteria was met. Additionally, the target was within the narrow FOV 100% of the time.

Using the subjective workload assessment technique (SWAT) in a head-to-head comparison with a non-MCG-guided AGM-130, a 25% reduction of WSO workload was demonstrated.

Subjective assessments of the value of the MCG modification were made using aircrew questionnaires and a modified Cooper-Harper Scale.

LIST OF SYMBOLS

AFB	Air Force Base
AGL	above ground level
AGM	air-to-ground missile
BLU	bomb live unit
CCF	Centralized Control Facility
C/A	coarse/acquisition
FOM	figure of merit
FOV	field of view
GBU	guided bomb unit
GPS	global positioning system
IMIRS	improved modular infrared sensor
IMU	inertial measurement unit
IMV	instrumented mockup vehicle
INS	inertial navigation system
LOS	line of sight
MCG	midcourse guidance
MITL	man-in-the-loop
nmi	nautical miles
PDOP	position dilution of precision
SWAT	subjective workload assessment technique
TM	telemetry
TSPI	time-space-position information
TVGS	television guidance seeker
USAF	United States Air Force
WAGE	wide area GPS enhancement
WGU	weapon guidance unit
WSO	weapon systems officer

1. INTRODUCTION

The AGM-130, like many standoff man-in-the-loop (MITL) munitions, is a demanding system to employ. Most of the demands placed upon the WSO occur when trying to locate the target area through the small seeker FOV in the midcourse phase of flight.

To assist the WSO in target acquisition, a closely coupled INS driven by GPS position and velocity updates has been added. This system guides the weapon during the midcourse phase and can point the seeker at the target. This modified weapon is referred to as AGM-130 MCG.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

2. WEAPON SYSTEM DESCRIPTION

The AGM-130 (Figure 1) was developed from the GBU-15 family of glide bombs. The primary difference between the GBU-15 and the AGM-130 is the addition of a rocket motor, radar altimeter, and digital autopilot. Both weapons are modular systems and can use either a 2,000-lb general purpose bomb (MK-84) or a penetrator warhead (BLU-109). The weapons are controlled via a radio frequency datalink with either an RT-1210/AN/AXQ-14 datalink pod. Both the current fielded versions of the GBU-15 and the AGM-130 use either a DSU-27 electro-optical or a WGU-33 imaging infrared seeker. Recent testing has certified two new, more advanced seekers. Both the WGU-40 television guidance seeker (TVGS) and the WGU-42/B improved modular infrared sensor (IMIRS) will soon be fielded.

The weapon has three phases of flight: midcourse, transition, and terminal. During the midcourse phase, the seeker is slewed independently of the weapon platform. The only way the WSO can adjust the flightpath of the weapon in this phase is with discrete heading or altitude commands. In the transition phase of flight, the WSO has direct yaw control of the weapon via slew commands. In this phase, the WSO still has no direct control over pitch. The final phase is the terminal phase in which the weapon platform steers, in both pitch and yaw, in response to seeker slew inputs. See Figure 2 for a typical low-altitude launch profile.

The MCG upgrade provides the WSO with the existing basic weapon capabilities and a significant increased capability for target acquisition, especially under adverse weather conditions. The MCG upgrade will also support the attack of horizontal targets - a capability not currently available in the fielded system.

During preflight, the weapon will be loaded with the GPS cryptokeys. The cryptokey comes on a tape that is read by a KOI-18 tape reader. The KOI-18 will then transfer the key to a KYK-13 or CYZ-10 for loading the weapon. A position update may be initiated using an AN/PSN-11 precision lightweight GPS receiver to speed up the inertial measurement unit's (IMU) alignment. Target coordinates, approximate launch coordinates, alignment data, and desired impact angle are loaded by slewing the target designator control (Figure 3). This obviates the need for developing an expensive capability for loading this data using the aircraft's 1760 Bus. Using the same method, targets may be reprogrammed inflight.

In captive or free-flight with the weapon operating normally, the WSO would see one of five messages: GOOD, MANUAL, FAIL, NO KEY, or NO SAT. The primary mode of operation is with GOOD displayed. In this mode, the weapon would navigate to the target coordinates and point the seeker at the target. When GOOD is displayed, the weapon could autonomously (no WSO inputs) navigate to and impact the target with GPS/INS accuracies.

The secondary mode of operation is MANUAL. This mode indicates that the INS is not using the GPS navigation solution due to figure of merits (FOM) not meeting the appropriate criteria. If the weapon is launched with MANUAL displayed, the autopilot would not use the INS for navigation (it would use a heading hold mode) nor would it point the seeker to a set of target coordinates. If the weapon is launched in MANUAL and the GPS signal improves, a launch point re-initialization may occur and the weapon will upgrade to GOOD. If the weapon degrades to MANUAL after being launched with GOOD displayed, the autopilot would still use the INS navigation solution and fly to a set of coordinates. When the system degrades to MANUAL after loss of GPS, seeker pointing would also still be available. However, the navigation solution would be based strictly on the INS solution with no GPS updates (degraded accuracy).

The worst case is for the weapon to be in a mode with FAIL displayed. This indicates a shutdown of the IMU, resulting in a totally inoperative weapon.

A NO KEY message indicates that a GPS cryptokey has not been loaded, and a NO SAT message indicates that the GPS receiver has not yet started to track satellites. Figure 4 shows the FOMs required for a GOOD to be displayed at different times-to-go.

The MCG kit includes a GPS antenna, a GPS receiver, an INS, and an autopilot.

The GPS receiver sent accurate position and velocity to the INS. This receiver used only the L1 frequency, which provided time, position, and ephemeris data for each satellite being tracked.

The INS provided a navigation solution to the autopilot. The Kalman filter imbedded in the INS used inputs from both the GPS receiver set (positions and velocities) and the inertial measurement unit (position/attitudes, velocities/rates, and accelerations) to provide the best navigation solution to the autopilot.

The autopilot calculated both a guidance solution and a stability solution based on inputs from the INS, IMU, and radar altimeter. During the midcourse and transition phases of flight, the autopilot relied on the INS and radar altimeter to provide a guidance solution based on zeroing the line of sight (LOS) angles/rates to the target and maintaining a programmed/ commanded altitude. During terminal flight, the autopilot used proportional navigation to guide to the target by zeroing the LOS rate to a given target coordinate, guiding the seeker lock-on designation, or guiding to a manually selected seeker crosshair location. The autopilot used information directly from the inertial measurement unit during all phases of flight to provide a stability solution to maintain a level weapon platform.

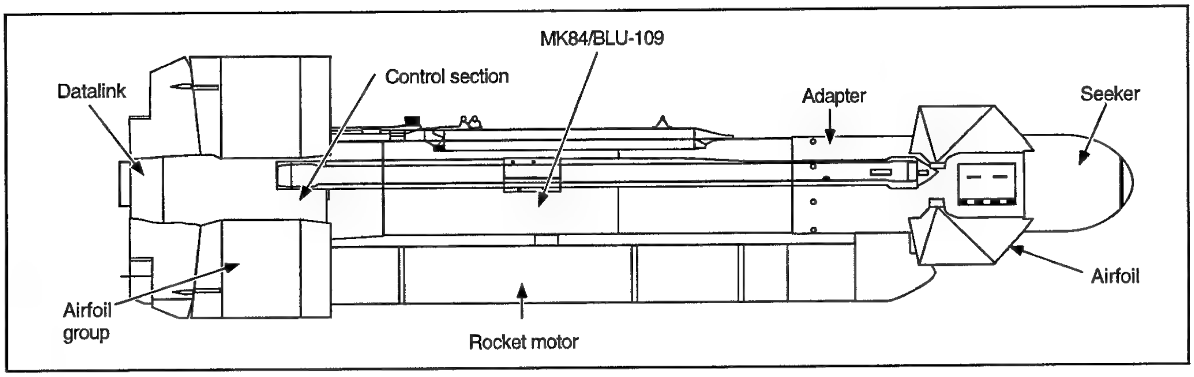


Figure 1. AGM-130

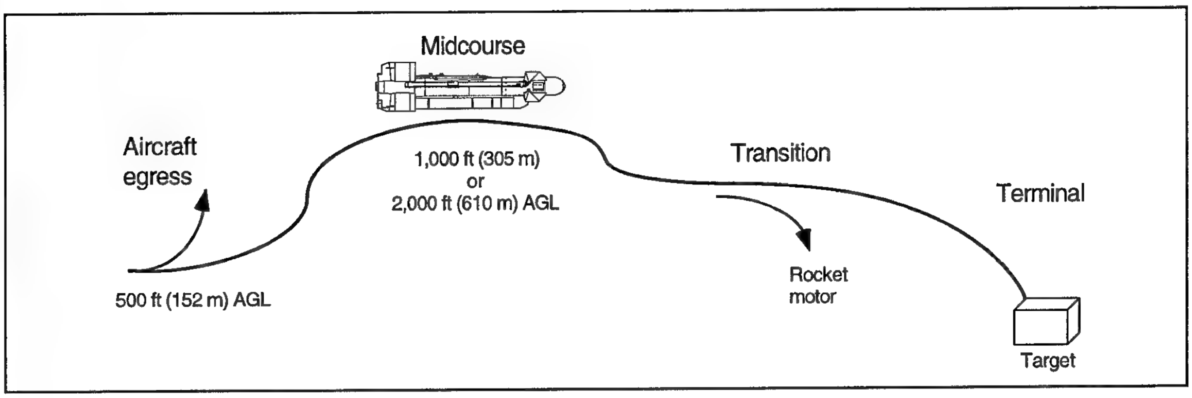


Figure 2. Typical Low-Altitude AGM-130 MCG Profile

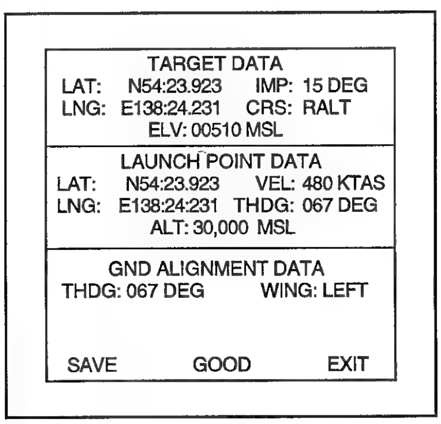


Figure 3. AGM-130 MCG Targeting Page

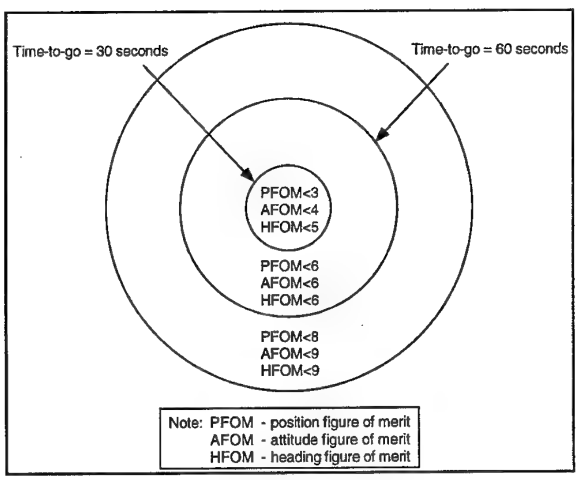


Figure 4. MCG GOOD/MANUAL Criteria

The WAGE weapon modified the MCG kit with a different GPS receiver. It used a second frequency, L2, which provided the same information as the L1 frequency. By receiving satellite data over two frequencies, the GPS receiver software was better able to compensate for timing errors due to propagation through the atmosphere. Additionally, the WAGE-specific GPS message sent from the appropriate satellite included updated GPS clock and ephemeris data. By incorporating a dual band antenna and receiving the additional WAGE messages, the receiver set was able to calculate a near differential position and velocity solution for the INS.

The WAGE missions were only a demonstration and there are no current plans to field an AGM-130 with WAGE modifications.

3. FLIGHT TEST METHOD

The AGM-130 MCG Phase I test program consisted of 3 ground function tests, 14 captive flights, and 3 live launches. The AGM-130 MCG Phase II test program will evaluate the system's ability to attack horizontal targets and is scheduled to begin in fall 1996.

Eglin AFB was selected for this test program because of its unique capabilities for standoff weapons testing. Eglin's large land and water ranges provide a realistic environment for testing weapons at significant standoff ranges. Eglin AFB also possesses a series of operationally realistic tactical targets, including hardened aircraft shelters, bunkers, surface-to-air missile sites, and buildings. Finally, Eglin was able to provide a Centralized Control Facility (CCF) that was capable of receiving, processing, and displaying, in real-time, all aircraft, weapon, and pod telemetry (TM). Additionally, the CCF provided real-time positive control of the test aircraft for safety-of-flight and would command the destruction of the weapon if necessary. The CCF also processed differential GPS signals, thus providing real-time time-space-position information (TSPI) to the required accuracies.

The ground functional tests evaluated system functionality with all possible configurations of seekers and datalinks.

The captive flights consisted of an F-15E loaded with an AGM-130 MCG instrumented mockup vehicle (IMV) and an AXQ-14 datalink pod making repeated passes against selected tactical targets. The IMV exactly duplicated a live weapon in all respects except for actual separation from the aircraft. With an IMV, the aircrew could actually pickle the weapon and simulate free-flight of the munition. This was done by having the aircraft fly the weapon's attack profile. Truth data was obtained through the use of differentially corrected GPS pods. Three of the captive carries were dress rehearsal missions prior to launches. The objective of these missions was to provide a realistic practice for all members of the test team including the test aircrew, chase aircrew, safety engineers, and test engineers.

The captive-carry weapon was also equipped with a flight-test-only modification to allow removal of the GPS signal. Launches would be made with the weapon in GOOD status. The GPS signal would then be removed. The degradation of the weapon's ability to accurately guide itself was then monitored. The next launch was made with the weapon in MANUAL status. Immediately following launch, the GPS signal was restored. The improvement in the weapon's ability to guide itself was then monitored.

Immediately following each mission, the WSO filled out an aircrew questionnaire with workload ratings from the modified Cooper-Harper Scale. With this and the aircrew's flight test report, a qualitative assessment of aircrew workload and other human factors issues were made. The modified Cooper-Harper Scale used can be found in Figure 5.

On seven of the captives, two passes were flown against first-look targets. These passes were used in conjunction with SWAT to determine a quantitative level of WSO workload reduction. These tactical targets had never been seen by the WSOs, except for photographs used in mission planning. The first pass was flown with the weapon set to MANUAL, thus essentially providing an AGM-130 without a MCG guidance capability. The second pass was flown using the full capabilities of the MCG weapon.

SWAT is a subjective technique used to gather quantitative data on workload. It evaluates workload using time, mental effort, and psychological stress as the factors. Four WSOs participated in the study. A group workload scale factor was used with psychological stress being the most important factor, followed by mental effort and time, respectively. Psychological stress is defined as the anxiety level of the WSO while he is guiding the weapon. Mental effort is defined as the amount of concentration required to guide the weapon. Time is defined as the amount of time spent on the task of guiding the weapon. The importance of each factor was determined from the WSO's sort of the 27 SWAT cards prior to the testing. These cards represented all combinations of the three factors and each WSO sorted them in the order of importance to them. Following each pass, the WSO would call out a rating for the three areas. Ratings went from 1 (easiest) to 3 (most difficult). Based on the card sorts, a numerical rating between 1 and 100 was calculated. One is the easiest and 100 is the hardest.

Following the mission, these numbers would be input into software and developed by the USAF's Armstrong Laboratories. By comparing a WSO's values for each pass with the card sort numbers, one can obtain a quantitative assessment of WSO workload reduction.

A dedicated mission was flown to test the system's ability to operate using coarse/acquisition (C/A) code with no cryptokeys.

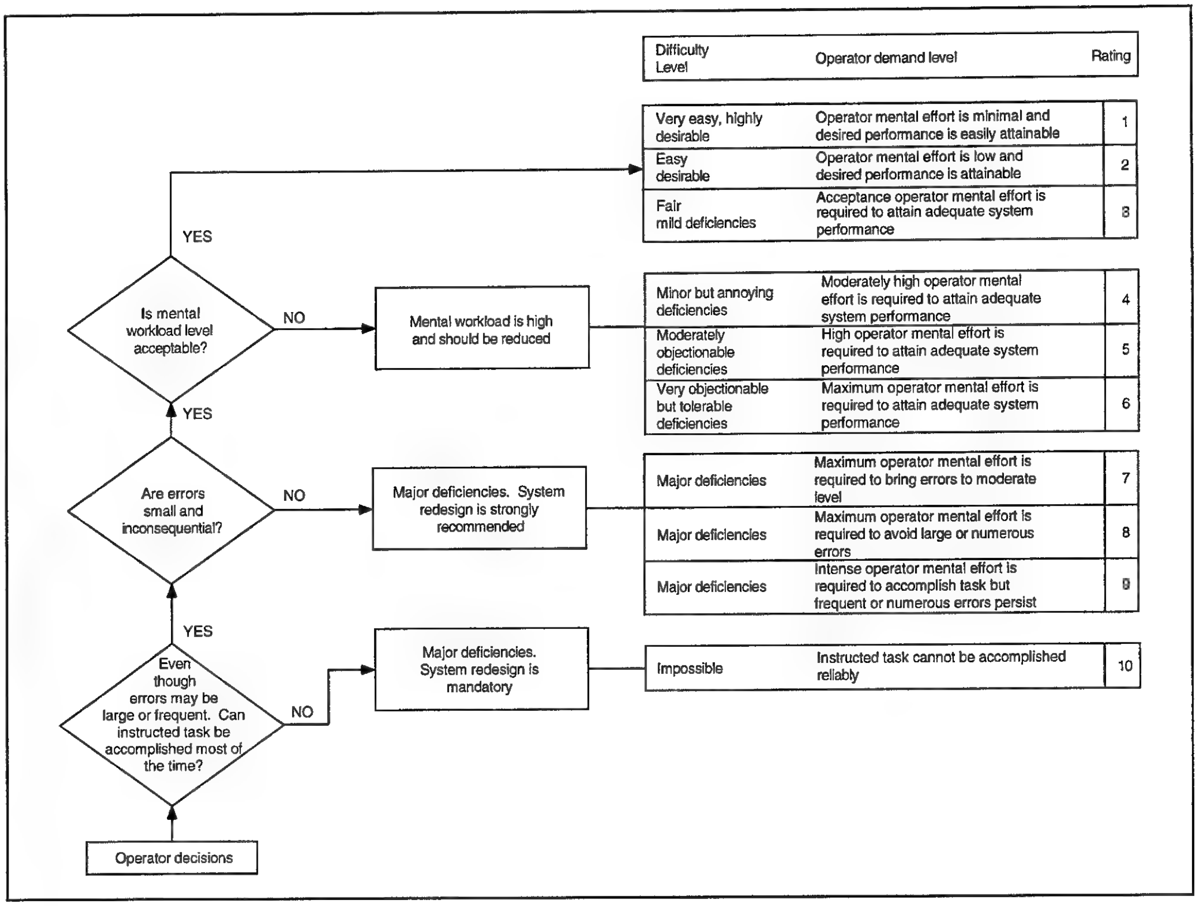


Figure 5. Modified Cooper-Harper Scale

On launch missions, a minimum of three passes were executed, denoted alpha, bravo, and charlie. On the alpha pass, various weapon functions were checked with TM and radio communications were confirmed between the test aircrew, chase aircraft, and the test engineer at the CCF. Weather minimums were also checked on this pass.

On the bravo pass, a power changeover from aircraft to weapon battery power was made and a practice pass over the target was performed. The safety engineer conducted a TM check of the flight termination system destruct signal and directed the range controller to ensure no personnel were within the weapon profile. The radar TSPI trackers and cinetheodolites performed system checks on the alpha and bravo passes and recorded data on the charlie pass.

The charlie pass was the weapon release pass. The aircraft controller in the CCF adjusted the standoff range based on winds and vectored the aircraft onto the run-in heading. The aircrew launched the weapon, performed an egress maneuver, and the WSO controlled the weapon to impact. The safety chase followed the AGM-130 after launch. The high-speed impact cameras ran when the weapon entered the camera's FOV.

4. FLIGHT TEST RESULTS

4.1 Subjective Workload Assessment Technique

Four WSOs participated in the SWAT study over seven missions. Using the WSO's card sort, a workload level of 58.57 was determined for the non-MCG AGM-130. Similarly, a workload level of 33.93 was determined for the MCG AGM-130. This represents a workload reduction of 24.64%—a significant reduction in WSO workload.

4.2 GPS Pointing Accuracy

The GPS-cued seeker pointing performance was critical to WSO workload reduction by pointing the seeker at the target. GPS-cued seeker pointing performance was satisfactory. The target was within the seeker's wide FOV 100% of the time. The seeker was pointed to within 1 degree (2 degrees overall) 80% of the time. Figure 6 shows the maximum probability of the

target being outside the seeker's FOV at different confidence levels. The test results indicate that there is a 95% probability that the target will be in the FOV at the 95% confidence level.

4.3 GPS Pointing Accuracy with C/A Code

The GPS-cued seeker pointing performance with C/A code was satisfactory. The target was within the seeker's wide FOV on all passes. The seeker was pointed to within 1 degree (2 degrees overall) 60% of the time. Figure 7 shows the maximum probability of the target being within the seeker's FOV at different confidence levels.

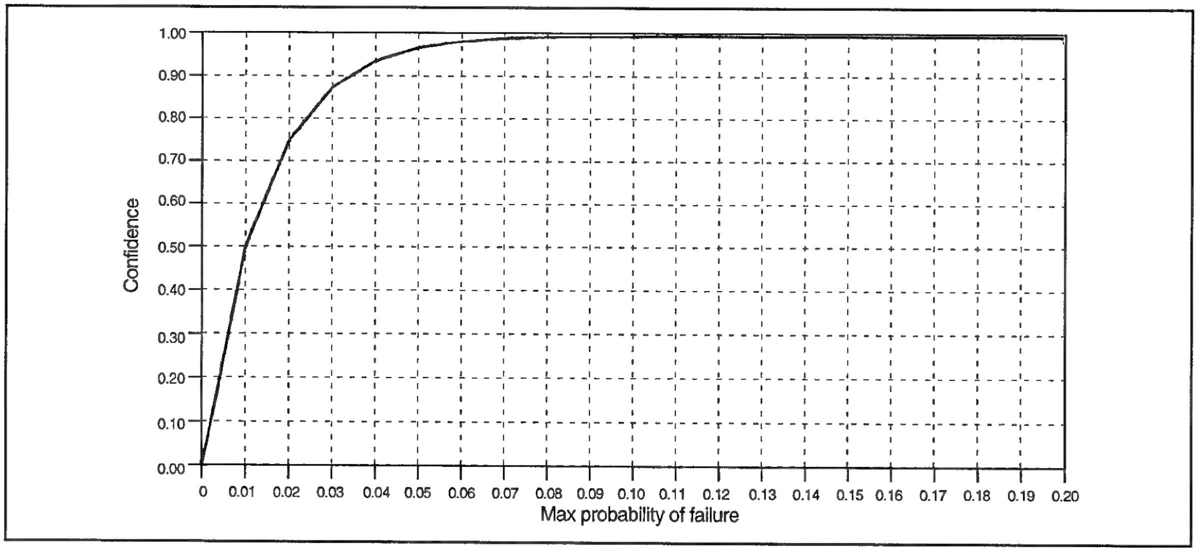


Figure 6. GPS-Cued Seeker Pointing Accuracy

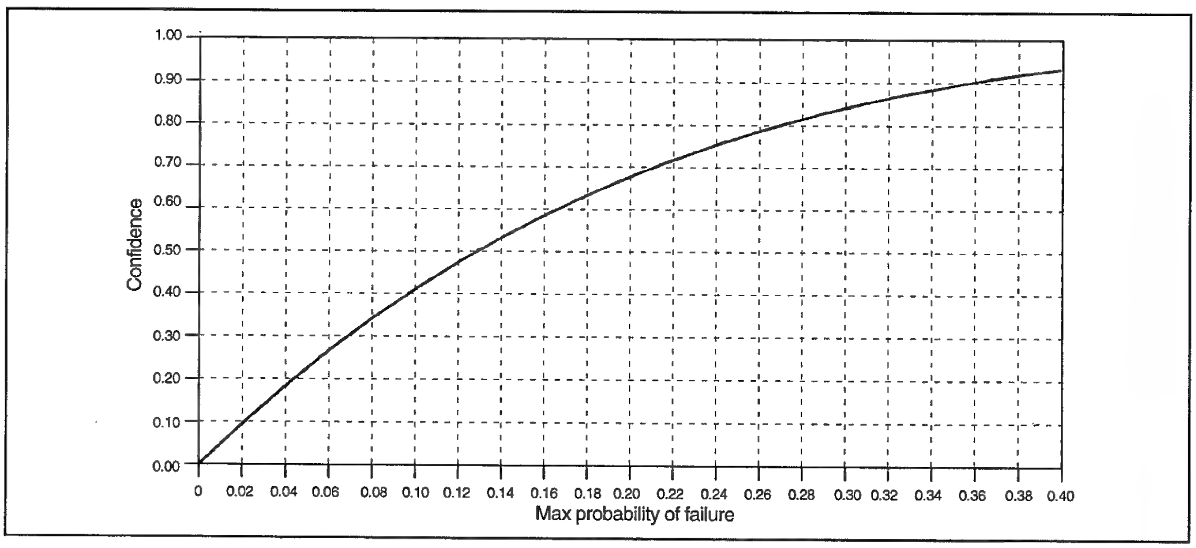


Figure 7. GPS-Cued Seeker Pointing Accuracy (C/A Code)

4.4 MCG Navigation Accuracy

An autonomous MCG capability allowed the WSO to perform additional crew duties and still accurately guide to the target. The navigation performance was satisfactory. The weapon GPS receiver set rarely tracked the optimal combination of satellites while being captive-carried. This was due to aircraft masking. The weapon GPS receiver tracked the optimal combination of satellites while in free-flight. The tracking state was satisfactory. The INS FOMs indicate the quality of the weapon INS estimates was also consistently optimal. Figure 8 shows the mean navigation accuracy and standard deviation for each pass. Figure 9 gives the overall mean navigation accuracy and standard deviation.

The WAGE navigation performance was satisfactory. In captive flights, the GPS antenna rarely tracked the optimal set of satellites due to aircraft masking. The weapon GPS receiver set correctly tracked the optimal combination of satellites in free-flight. This combination gave the lowest position dilution of precision (PDOP). The tracking state was optimal. The INS FOMs indicate the quality of the weapon INS estimates was also optimal. Postmission data analysis shows that the weapon consistently estimated its position lower than its actual altitude. This indicates that a consistent guidance system altitude error was not corrected. Figure 10 shows the mean navigation accuracy and standard deviation for each pass with the WAGE weapon. Figure 11 gives the overall mean navigation accuracy and standard deviation for the WAGE weapon.

It should be noted that postmission analysis demonstrated that the implementation of WAGE was not optimal. This was attributed to modifying an existing weapon design rather than designing a new weapon to take full advantage of the improved accuracies available with WAGE corrections.

4.5 MCG Navigation Accuracy with C/A Code

The navigation performance with C/A code was satisfactory. The weapon GPS receiver set consistently tracked the optimal combination of satellites. The tracking state was consistently optimal. The INS FOMs indicate the quality of the weapon INS estimates were also consistently optimal. Figure 12 shows the mean navigation accuracy and standard deviation for each pass with C/A code. Figure 13 gives the overall mean navigation accuracy and standard deviation with C/A code.

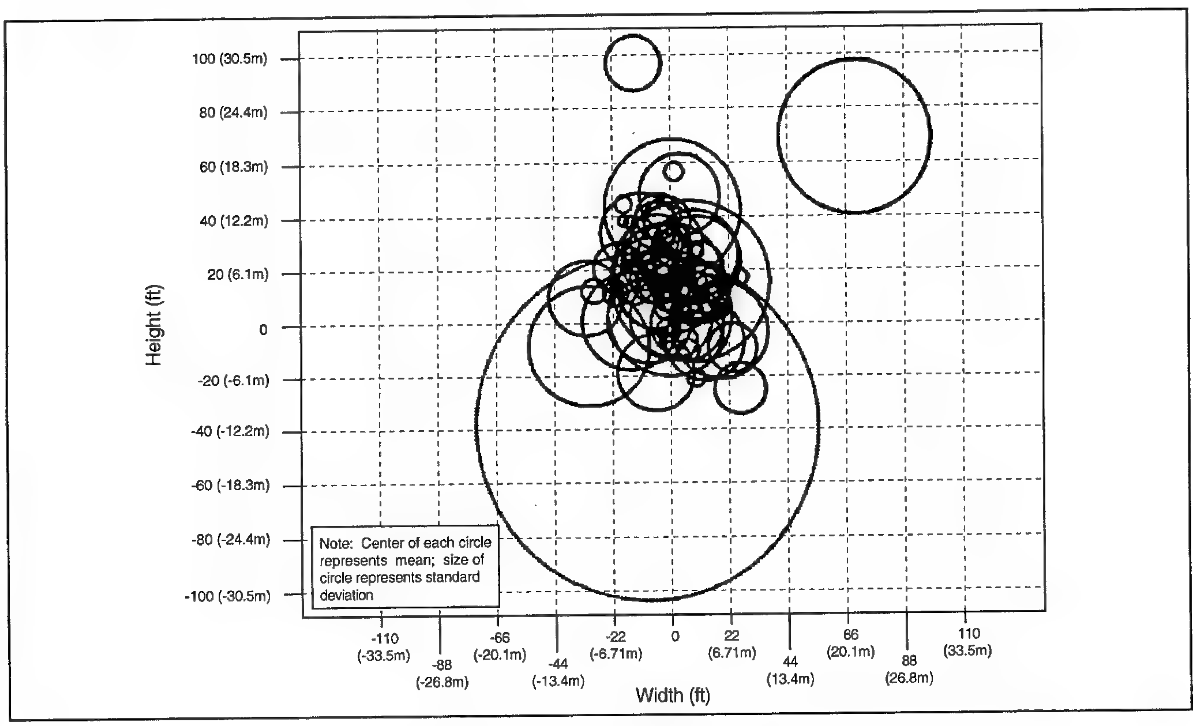


Figure 8. Individual Pass Navigation Accuracy

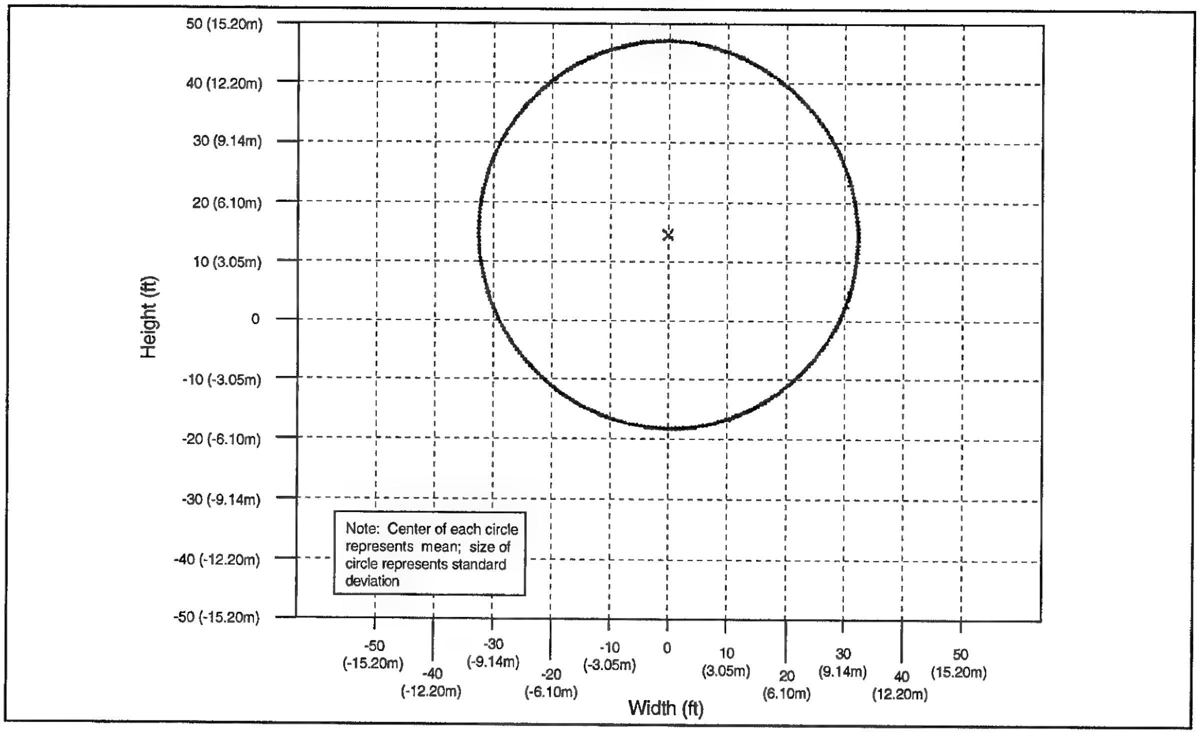


Figure 9. Overall Navigation Accuracy

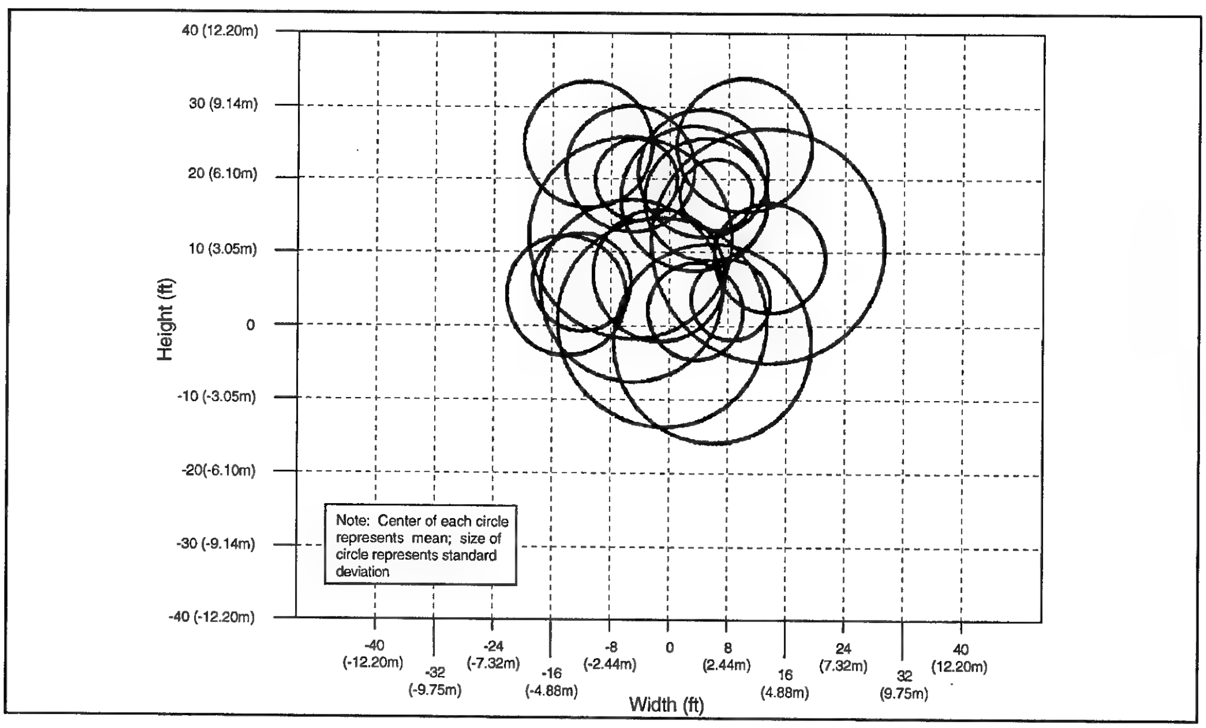


Figure 10. Individual Pass WAGE Navigation Accuracy

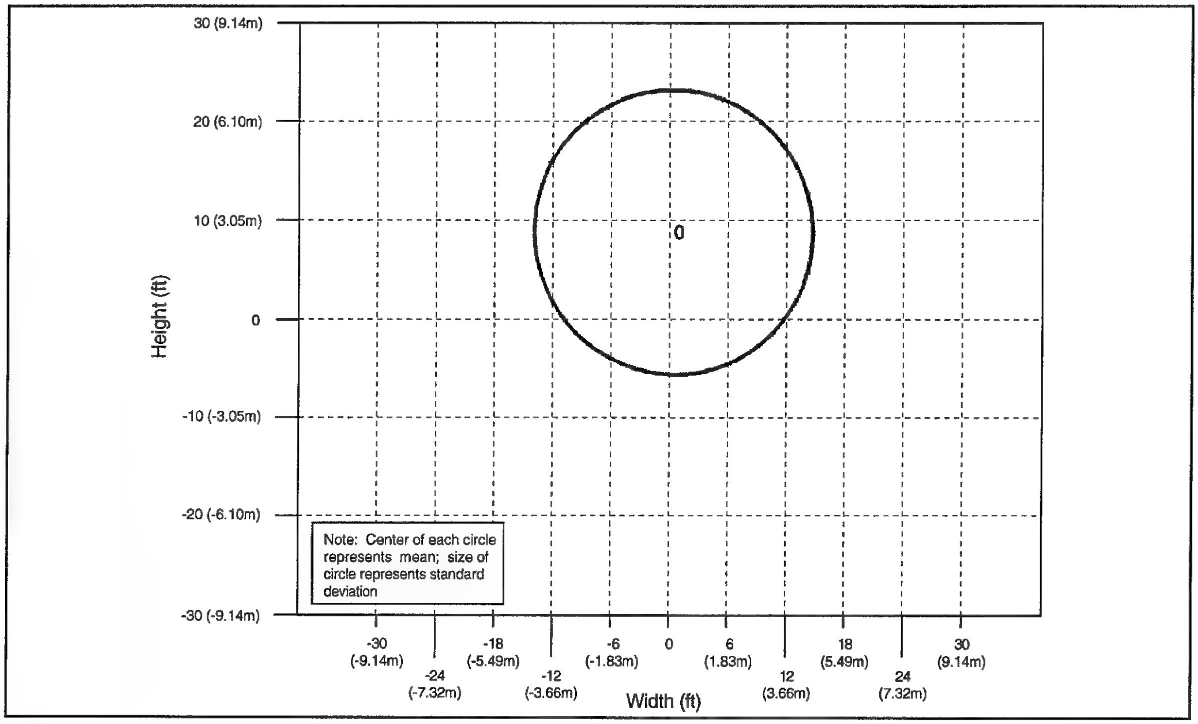


Figure 11. Overall WAGE Navigation Accuracy

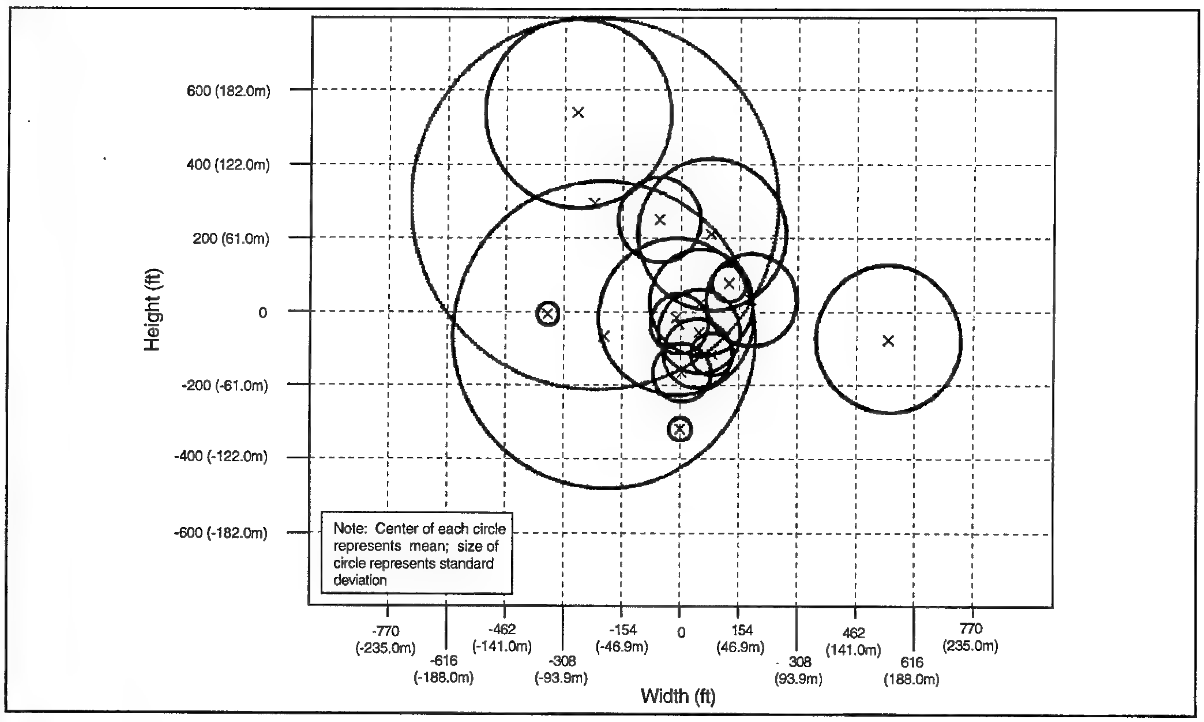


Figure 12. Individual C/A Pass Navigation Accuracy

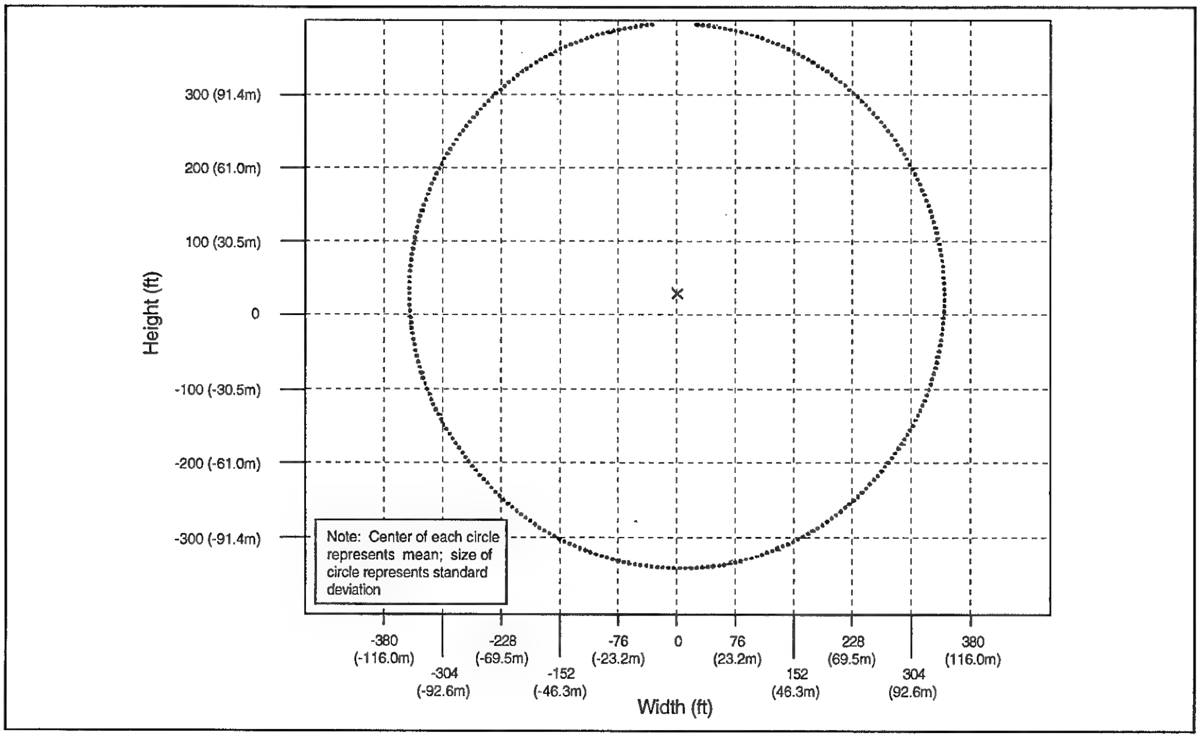


Figure 13. Overall C/A Code Navigation Accuracy

4.6 Live Launches
Table 1 lists the desired launch conditions for each of the live launches.

Table 1. Desired Launch Conditions

Launch	1	2	3
Seeker	TVGS	IMIRS	TVGS
Heading	235 deg true	268 deg true	237 deg true
Altitude	1,000 ft AGL (305 m)	5,000 ft AGL (1,524 m)	2,000 ft AGL (610 m)
Airspeed	480 KTAS	520 KTAS	480 KTAS
Range	13 nmi (24.1 km)	16 nmi (29.6 km)	13 nmi (24.1 km)
Bank	0 deg	10 deg	0 deg
Notes		10-deg offset heading, auto terminal	WAGE hands-off launch

4.6.1 Launch 1
The objective of the first launch was to demonstrate accurate guidance, navigation, and GPS-cued seeker pointing. The weapon was successfully launched within tolerances and satisfactorily impacted the target. The weapon was launched under datalink control and GPS pointing was engaged immediately after release. The WSO periodically slewed throughout the profile, then returned to GPS pointing. The WSO-commanded transition and terminal occurred at 17 seconds time-to-impact. The WSO manually guided the weapon to impact.

The guidance and navigation performance of the weapon was satisfactory. The weapon GPS receiver made no constellation changes and stayed in the State 5 track state. During free-flight, the receiver processed the optimal number of 4 pseudorange and 4 pseudorange rate values. The INS FOMs were low, indicating that the quality of the weapon INS was optimal. An extrapolation of the weapon INS estimate from the time the WSO intervened to impact indicates that the position estimate was less than 20 ft (6.1 m) off at impact.

Weather for the launch was marginal with a cloud deck at 1,500 ft (457 m) AGL and a considerable amount of haze. Because of this, the WSO initially identified the wrong target, but corrected his error when MCG pointed the seeker at the correct target.

4.6.2 Launch 2
The second launch was intended to be an endpoint demonstration of the increased capability gained in employing an AGM-130 with MCG. The weapon was launched within tolerances and satisfactorily impacted the target. The launch

profile was changed to add 4 decrements to get below a 1,500-ft (457-m) cloud ceiling. The launch point was moved approximately 1 nautical mile (1.85 km) closer to the target to correct for a significant headwind. The weapon was launched under datalink control with a 10-degree heading offset and 11 degrees of bank. Immediately after launch, GPS pointing was commanded. The weapon automatically corrected its course. At 21 seconds time-to-impact the WSO locked onto the target. The weapon went autoterminal at 15 seconds time-to-impact.

Impact occurred after 118.5 seconds time-of-flight. An unusually large miss distance is attributed to the seeker correlation tracker drifting due to low contrast at approximately 4 seconds time-to-impact.

The guidance and navigation performance of the weapon was satisfactory. The weapon GPS receiver made no constellation changes and stayed in the State 5 track state. During free-flight, the receiver processed the optimal number of 4 pseudorange and 4 pseudorange rate values. The INS FOMs were low, indicating that the quality of the weapon INS was optimal. An extrapolation of the weapon INS estimate from the time the WSO intervened to impact indicates that the position estimate was less than 160 ft (48.8 m) off at impact. The large error, compared with previous sorties, is the result of an unusually high PDOP for the launch.

This launch was the most challenging ever attempted by an AGM-130. Not only was the ceiling low and the visibility poor, but there was considerable precipitation the previous 24 hours. This made for extremely poor infrared conditions. Additionally, the selected target was a simulated SA-3 site hidden in a wooded area. The adverse weather combined with the challenging launch profile truly demonstrated the increased capability of MCG for standoff weapons. The target actually broke out from the surrounding clutter at less than 25 seconds time-to-impact.

4.6.3 Launch 3

The third launch, with the modified WAGE-capable weapon, was successfully launched within tolerances and satisfactorily impacted the target under its own internal guidance. The launch profile was changed to 1,000 ft (305 m) AGL cruise due to a cloud deck at 1,500 ft (457 m) AGL. The weapon was launched under datalink control with GPS pointing engaged. The WSO remained hands-off for the entire flight with the exception of a planned demonstration of manual seeker slewing and GPS pointing 20 seconds after launch. The autopilot commanded autoterminal at 15 seconds time-to-impact. The weapon impacted the target 96 seconds time-of-flight. It missed the intended point of impact by 25.3 ft (7.71 m).

The WAGE navigation performance was satisfactory. The weapon GPS receiver set correctly tracked the optimal combination of satellites. This combination gave the lowest PDOP. The tracking state was optimal. The INS FOMs indicate the quality of the weapon INS estimates were also optimal. The weapon hit the target above the target aimpoint coordinates. Postmission data analysis shows that the weapon consistently navigated to a point higher than the target aimpoint. This indicates that a consistent guidance system altitude error was not corrected.

The WAGE guidance performance was satisfactory. The weapon guidance error was less than 2 ft (0.61 m). Postmission analysis shows that the autopilot guided the weapon within 2 ft (0.61 m) of the INS estimate of the target aimpoint coordinates.

5. CONCLUSIONS/LESSONS LEARNED

The following are the important conclusions demonstrated by the AGM-130 MCG Phase I test program:

1. The AGM-130 MCG weapon system significantly reduces WSO workload and increases target acquisition capability.

2. The AGM-130 MCG provides increased operational utility with the improved capability to strike in low visibility conditions and to accurately retarget while the aircraft is airborne.

3. The AGM-130 MCG, when used in conjunction with either the TVGS or IMIRS seekers, provides for a significant increase in detection ranges (at day or night) and improves the ease of operation at increased aircraft launch distances.

4. Standoff MITL weapons can benefit greatly with a MCG capability.

5. MITL weapons provide an added benefit of instant bomb impact assessment and bomb damage assessment over autonomous systems.

6. REFERENCES AND ACKNOWLEDGMENTS

For reference materials and acknowledgments, please contact your AGARD liaison.

HELICOPTER CERTIFICATION - THE CHALLENGE OF TESTING UK APACHE

Roger S. Finch

Manager, Performance & Flying Qualities Section
Rotary Wing Aircraft Department
Defence Test & Evaluation Organisation (DTEO)
Boscombe Down, Salisbury, SP4 0JF,
England

SUMMARY
In July last year the UK Government announced the eagerly awaited decision on the UK Army's future Attack Helicopter (AH). The UK would purchase 67 WAH-64 APACHE helicopters, a derivative of the McDonnell Douglas Helicopters AH-64D Apache. The aircraft would be produced by GKN Westland Helicopters Ltd, as the Prime Contractor, with McDonnell Douglas Helicopter Systems as the Integrating Sub-Contractor. The WAH-64 would be fitted with a version of the Rolls Royce-Turbomeca RTM 322 engine, currently fitted to the UK's Merlin helicopter. The paper presents an overview of the emergent technologies being considered for the UK Apache, in particular a Defensive Aids Suite (DAS) and Helmet Mounted Displays (HMD). Ideas on a future handling qualities assessment are also presented. Before the first UK Apache arrives at Boscombe Down for clearance testing, the UK Test & Evaluation (T&E) community must develop the required clearance methodologies to evaluate the aircraft as a complete weapons system: preliminary work addressing this issue has already started. Clearance testing will, undoubtably, make greater use of simulation, as well as placing more emphasis on joint testing with Industry. The challenge facing UK T&E is how to acquire the required test data with the minimum amount of testing to generate the evidence necessary for the aircraft's Military Aircraft Release (MAR).

1. INTRODUCTION

1.1 UK AH Competition Winner
In July 1995 the UK Government announced the winner of its Attack Helicopter (AH) competition - the Army Air Corps would receive 67 Apache helicopters, all to the latest D model (ie Longbow) configuration. Entry into service would be at the end of the century. The aircraft would be produced by an industry team led by Westland Helicopters and would include McDonnell Douglas Helicopters (the Apache Design Authority) and Rolls Royce. The aircraft would be designated the WAH-64 Westland Apache - hereafter called UK Apache. The UK Apache would be fitted with a version of the Rolls Royce-Turbomeca RTM 322 engine, currently fitted to the UK's new Merlin helicopter.

1.2. Emergent Technologies applicable to UK Apache
The principle developments in military helicopter technology over the next 5 to 10 years will be in the application and integration of current and emergent technologies to achieve the most cost effective helicopter weapons system. This will require the helicopter to be understood as a total system, and evaluated in

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

an appropriate operational context. For future attack helicopters advances in blade and control technology will be required to provide sufficient care-free agility and manoeuvrability to bring weapons to bear on the intended target. (For UK Apache such advanced rotor blades and/or control technology could feasibly be part of a Mid Life Update).

However, as importantly and more near term are improvements in sensors, defensive aids, and information management systems which can provide the crew with timely piloting and tactical information for the required level of situational awareness for mission effectiveness and survivability. To do this information will have to be automatically prioritised and presented in such a way that it is easily assimilated. The AH-64D Longbow programme in the USA is a good example of developments of this kind. Arguably the most significant component in the system in the near term is the next generation of a visually coupled helmet mounted display (HMD) - often called the Integrated Helmet. This will permit all weather, day and night, operations whilst allowing the pilot to be "heads-up, eyes-out" viewing the outside world or a suitable representation of it overlaid with conformal tactical and navigation information, gathered by the aircraft itself and possibly augmented, via a digital data link, from other friendly units. At present most work on visually coupled sensors has involved thermal imagers, however, further developments may lead to the integration of image intensifiers, radar, and LIDAR sensors.

To enhance survivability on the battlefield, a comprehensive and highly automated Defensive Aids Suite (DAS) will need to be installed to cope with a wide range of threats, incorporating radar warning receivers, laser, IR, and UV detectors, appropriate jammers, decoys, and electronic countermeasures. A new DAS is being proposed for UK Apache, taking full advantage of all the latest relevant technologies.

1.3 Test & Evaluation Challenge

In the Test and Evaluation (T&E) community the test methods which have traditionally been used are rapidly becoming inadequate. The challenge for T&E is not only to develop new test methods which can enable such highly integrated systems to be evaluated, but also to reassess the way in which we go about our business. The formation of the Defence Evaluation & Research Agency (DERA) within the UK Ministry of Defence provides the UK with the opportunity to do this and to create organisational structures appropriate to the task.

1.4 Having briefly introduced some topics relevant to UK Apache, the paper addresses the subjects of DAS, future handling qualities and HMD in more detail. In particular the interaction between pilot mission related tasks and HMD in the context of the UK Attack Helicopter is reviewed.

2. DEFENSIVE AIDS SUITE

The effectiveness of self-protection for military platforms is one of the most important considerations of military operations. A main hazard affecting helicopter vulnerability is the use of weapons incorporating electro-optic guidance - depending on the source of data- 75% to 90% of all aircraft losses to hostile engagements over the last 25 years have resulted from such weapons [1]. As guided weapons proliferate and become more capable, so the need for protective countermeasures, particularly in peacekeeping deployments, increases. Vulnerability to such hostile weapons depends on platform signature, defensive countermeasures and aircraft manoeuvrability: signature control is intended to make the platform undetectable or at least to delay detection; when it fails, defensive countermeasures are directed to defeating the threating weapon and will often call up the assistance of some form of evasive manoeuvre.

The electro-optical guided surface-to-air (SAM) missile threat to aircraft is not new. However, SAM capability has vastly improved since the 1950s and significant progress has been made in reducing a helicopter's signature, from the simple suppression of the helicopter's engine exhaust to controlling every aspect of its infra-

red signature and at all angles of approach. The objective remains the same, to reduce the detection and lock-on ranges of the seeker, so permitting the helicopter more time to deploy countermeasures.

A parallel approach is to develop pyrotechnic decoy devices that are robust to the counter-countermeasures used in seekers of different generations and origins: it is becoming increasingly difficult to provide a reliable decoy that can counter all threat seekers. Decoys, in the form of flares are already fitted or being fitted to UK military helicopters (eg. Chinook and Sea King) along with chaff dispensers (eg. M130 countermeasures dispenser) to counter radar seeking missiles.

An alternative technique is to use an electro-optical (EO) jammer to upset the seeker and its associated guidance control. The jammers are based on lamp sources that are modulated either mechanically or electrically. Performance is determined by a number of factors, one of the most important being the jammer/signal ratio. If the signature of the platform can be reduced, the signal received by the threat detector will be reduced accordingly, and the same overall system performance can be retained using lower jammer power, so easing the demand on platform supplies. Whilst lamp sources are effective in the visible and near infra-red (IR), seekers will increasingly use the mid infra-red 3 to 5 micron waveband where lamps have low output. A solution here is to use lasers, which possess many characteristics which render them attractive for electro-optical countermeasure (EOCM) applications. Lasers will be used to dazzle, deceive, or damage sensors in each of the militarily-significant wavebands. Lasers offer much narrower bandwidth and divergence than established jammer lamp technologies, and may enable a wider range of seekers to be countered through the delivery of higher in-band power.
An example of the future generation of jammer, the Directed IR Countermeasure (DIRCM), is shown in figure 1.

In future attack helicopters, including UK Apache, DAS is likely to consist of a series of sensors, including laser and radar warning receivers and hostile fire and missile approach warners, together with countermeasures which may include IR and radar jammers, chaff and decoy flares. In principle, on detecting a threat, it is possible to deploy appropriate countermeasures automatically, although crew intervention may be preferable in tactically sensitive situations. In creating a DAS capability it is essential to look at the capability of the overall platform in the context of the expected threat and to consider interference with other systems - for instance, the addition of an EO jammer must not adversely affect the radar signature of the helicopter, and vice versa [2].

For UK Apache, an option currently being studied is to replace the existing ALQ-144 IRCM system with a DIRCM and possibly upgrade it with a laser at a later date. The choice of DIRCM and possibly other sensors to integrate into the UK Apache's Defensive Aids Suite (DAS) has yet to be finalised.

3. FUTURE HANDLING QUALITIES

3.1 New Handling Qualities Standard - ADS-33

In the selection of the Army's new attack helicopter, combat effectiveness and survivability were identified as important attributes that related directly to flight performance [3]. The UK AH had to be capable of conducting aggressive all-weather, ultra low level operations by day and night, with acceptable pilot workload. This requirement dictated that UK AH should be agile with a wide manoeuvre envelope. For the pilot to be able to exploit fully the available performance with a tolerable workload, the air vehicle would need to exhibit good handling qualities.

In the UK the mandatory requirements for the handling qualities design criteria of military helicopters have remained virtually unchanged for the last 30 years. During this time helicopter technology has made considerable advances and the role of military helicopters has become increasingly diverse and demanding. For the UK

Attack Helicopter missions, present handling criteria are considered to be inadequate as they are generally qualitative.

It has been recognised for some time that new flight test methods are needed which measure parameters which are directly related to the task the helicopter is to carry out. The results from traditional tests relate only indirectly to the ease or otherwise of carrying out specific tasks, and so may not reveal that the handling qualities of a helicopter are wholly unsuitable for a particular role. To overcome this problem the development of a new standard - Aeronautical Design Standard 33 (ADS-33) [4] - was initiated in the USA for their LHX (Comanche) programme. One of the most important contributions of ADS-33 is the acknowledgement that good basic flying qualities alone may not be adequate to perform a mission. The combination of the basic airframe, controls, visionic enhancement, weapon systems, environment and mission must be examined as a total system.

In the UK the Defence Research Agency (now part of DERA) have been closely involved in the ADS-33 effort since the early 1980s and has made a considerable contribution to the development of mission related flight test manoeuvres incorporated in ADS-33, through a major research effort utilising both the Advanced Flight Simulator (AFS) at Bedford as well as various research aircraft. In ADS-33 new test criteria such as Agility, Aggressiveness and Usable Cue Environment (UCE) are introduced and quantified.

The UCE criteria attempts to account for the fact that when flying near the ground in conditions of poor visibility, the pilot might need help from a more advanced flight control system than the one that is satisfactory when visibility is good. The best flying cue available to a pilot is a clear view of the horizon and everything around him. When the view is not clear - such as at night or in bad weather - his ability to perform flying tasks satisfactorily and safely is compromised.

The UCE is meant to quantify the degradation of view and numerical values of 1,2 and 3 represent good, fair and poor conditions respectively. The rating for a given helicopter and manoeuvre are based on a combination of the pilot's perception of how good he can visually judge roll and pitch attitude, horizontal translation rate, and vertical translation rate.

In ADS-33 the pilot handling qualities ratings are also scaled from 1 to 3. Level 1 represents satisfactory handling qualities and corresponds to a Cooper-Harper handling quality rating (HQR) of less than 3.5. With Level 2, adequate performance can be achieved but only at the expense of considerable pilot workload. Its upper limit on the HQR is 6.5. Above that comes Level 3, where adequate performance cannot be achieved. Figure 2 presents the Cooper-Harper HQR scale and its relationship to the ADS-33 handling qualities levels.

It is envisaged that ADS-33 will become widely accepted as the definitive standard for future helicopter flying qualities evaluations. Under the methodology which ADS-33 proposes the handling qualities required by an aircraft in a particular role are defined at the outset in a form which a manufacturer can use in his design process. Then when the aircraft is tested objective and subjective data is gathered which will show that the task performance and pilot workload requirements can be met with no handling qualities problems, if the specification has been met. It is fundamental within the standard that the helicopter is evaluated as a system for carrying out a particular role, without any assumption of size. Testing is straightforward in that quantitative boundaries are defined for measurable parameters, but it is implicit that the desired handling qualities and appropriate pseudo mission tasks are completely defined at the outset. This should enable fitness for role to be established against which future improvements may be identified.

Although ADS-33 is formally a US Army standard for the RAH-66 Comanche helicopter, it has been developed out of International Collaboration and, in its structure and form, is

applicable to all roles and types. The framework for using ADS-33 as a requirements capture, design and evaluation/qualification methodology is illustrated in figure 3. The detailed response type requirements follow from the user-defined missions and operational environments, and hence the UCE. Resultant handling qualities levels are judged on a combination of results from clinical open-loop and demonstration closed-loop test manoeuvres. The open loop testing is carried out to establish if the predicted quantitative handling quality levels are met. This embraces traditional flight test techniques, but expands these, to examine the aircraft response to small, medium and large control inputs and aircraft response to frequency sweeps. In pilot-in-the-loop testing, assigned subjective handling quality ratings, using the Level 1 to 3 HQR scale described earlier, are gathered from the pilot whilst flying pseudo-mission flight tasks - or Mission Task Elements. In addition the UCE is assessed, in a UCE 1 it is defined in ADS-33 that a rate demand system will be sufficient, however, as the UCE is degraded then there is a need for enhanced stability/display augmentation to obtain the required handling characteristics in the specified Degraded Visual Environment operations.

The final testing consists of role tests and, as with the earlier tests, it is necessary to instrument the aircraft and carry out the tests under telemetry control. This is necessary to monitor stresses and loads to ensure that load and fatigue limits are not exceeded. Typically tailcone bending, tail and main rotor flap, and pitch links must be monitored. Although, loads should be within limits, the test aircraft fatigue spectrum will be quite different to that envisaged for actual operations. Also to ensure that flight envelope limitations are not exceeded telemetry is used to ensure that damaging airframe or rotor modes are not excited which might not be observed by the crew. For the handling qualities and visual cue rating tests a minimum of 5 pilots from similar and appropriate operational backgrounds are required to ensure Handling Qualities Ratings (HQR) consistency. For accurate assessment of the mission task elements precise flightpath tracking is required from differential GPS information or some other system.

3.2 Test & Evaluation Clearance Issues

A helicopter designed to, and complying with, the ADS-33 standard should exhibit very good handling qualities in service. ADS-33 states that a helicopter should exhibit level 1 handling qualities (desired performance consistently achievable at low pilot workload) throughout the operational flight envelope. In this sense the standard has to be seen in the context of high levels of flight control augmentation, that tame the natural tendencies typified by the lack of carefree handling, strong cross couplings and poor stability. Because the standard was developed specifically for the Comanche, this means that there is no aircraft in service which has been designed under the ADS-33 philosophy, and consequently as the Comanche design requirements are more demanding than for previous aircraft, it is the only aircraft which is likely to meet the ADS-33 requirements. The question then arises as to what value is ADS-33 in evaluating the capabilities of existing helicopters or more generally helicopters not designed to this Standard? The question is particularly relevant to the UK Apache. Research experience to date suggests that most current operational helicopters exhibit a wide range of Level 2 characteristics combined with some Level 1 and even Level 3 characteristics. A Level 2 helicopter can still perform missions with adequate performance but the pilot is likely to have to work harder to compensate for deficiencies. The ADS-33 standard has been developed to discern helicopter flying qualities across all three Levels, and hence is properly applicable to existing aircraft as well as super-augmented aircraft of the future, in both normal and failed conditions (where some degradation into Level 2 and 3 is allowed). Within the T&E community the challenge is to take ADS-33 from the research environment into the test environment. This initially involves an education process to ensure that the new tools are applied appropriately, and the results correctly interpreted. For example if it is found

that HQRs are highly scattered then the flight test was poorly defined, or the backgrounds of the pilots used were too different. It is important that this is correct because of the fundamental part pilot subjective ratings play in ADS-33 testing. Also, ADS-33 is not a replacement for traditional methods but an extension of them, so its implementation may require more resources, and a greater level of instrumentation and real-time data evaluation as described above. DTEO Boscombe Down believe there is potential to subject UK Apache to ADS-33 type testing to quantify the aircraft's handling qualities and thus identify any potential shortfalls. UK Apache is intended to operate for the first 30 years of the 21st century and an ADS-33 type evaluation will identify and quantify the aircraft's capabilities against a number of mission profiles. This will establish its fitness for the role as well as forming a baseline against which requirements for future improvements can be identified and developed in the most cost effective manner.

4. HELMET MOUNTED DISPLAYS VISUAL COUPLED SYSTEMS

4.1 VCS - General

One of the most significant items of equipment in future attack helicopters will be helmet mounted displays (HMD). The development of these is an area of intense activity at the moment. There are many issues and problems which need to be solved before they reach service however. Initially the concept was to provide a display similar to that of a head up display (HUD), but it has now been carried much further than that by the drive to provide day/night all weather capability through the use of visually coupled systems (VCS).

Modern attack helicopters are increasingly using VCS to give a day/night, all weather capability in the Nap-Of-The-Earth (NOE) environment. The basic system comprises a head-position sensor, a helmet mounted display (HMD) and an electro-optical imaging sensor (frequently a Thermal Imager (TI)) mounted on a gimbal system, with a symbol generator and display (figure 4). In operation, the imager is automatically pointed in the direction of the crewman's head and the image is projected on his HMD.

4.2 VCS - UK Apache

On the UK Apache (and the US Army AH-64), VCSs are provided for both crew in the tandem seat aircraft, the imaging sensors being positioned in the nose. The two independent systems, the Target Acquisition Designation Sight (TADS) and the Pilot Night Vision Sensor (PNVS) provide day/night and limited adverse weather targeting and night navigation capabilities. The TADS provides the co-pilot/gunner with capabilities for target search, detection, recognition, and laser designation by means of direct view optics, television and forward looking infrared sensors that may be used singly or in combination depending on tactical or weather/visibility conditions. The PNVS provides the pilot with thermal imaging capabilities that enable nap-of-the-earth flight to, from, and within the battle area at night, at altitudes low enough to avoid detection by the enemy. The outputs from these sensors are presented on multi-function displays (MFD) in both cockpits and/or on the aircrew's helmet mounted Integrated Helmet & Display Sight System (IHADSS). The IHADSS tracks each crew member's helmet, provides helmet position data to the weapons processor, and processes video for display to the crew.

When flown operationally, the TADS/PNVS system has proved valuable in extending the conditions in which helicopters can be employed. The system potentially offers both pilot and gunner significant increases in flexibility and mission effectiveness. The IR camera gives the capability to see at night and in some bad weather conditions when viewing is far clearer than directly with the human eye. The display symbology may be task driven, either manually or automatically, to give both crew members all the information they need during almost all of the mission without needing to look into the cockpit.

4.3 Night Vision Goggles

In the UK's current military helicopters, Image

Intensifier (II) equipped Night Vision Goggles (NVG), attached to the aircrew's helmets, play an increasingly important role in extending the aircrew's ability to see and thus operate at night. Their main limitations are light level, natural ground contrast and severe overloading by bright lights (so called "blooming"). Bad weather has much the same effect on II systems as on the human eye, that is the reduced night visual acuity and acquisition range. The next evolution process for NVGs is digitising their images and then integrating them with other on-board systems (such as a TI mentioned earlier) for direct viewing by the aircrew. Thus helmet attached NVGs will give way to Integrated Helmets (eg. The Franco-German Tiger and the US RAH-66 Comanche aircrews will be provided with Integrated Helmets as standard equipment).

4.4 Integrated Helmet

Thus, in a truly Integrated Helmet, all available sensor information (ie. IR,II,and TV) will need to be brought together and displayed in an appropriate form. It is vital that the information is displayed to the crew in a manner that can be readily assimilated. When operating NOE, aircrew must be able to spend as much time as possible looking out of the cockpit. Although the HMD supports this "head-up, eyes-out" philosophy, the HMD is limited in the amount and type of information that can be effectively presented. The conventional multi-function head-down display provides a complementary medium, which enables such information as route plans and long range data to be shown as terrain-referenced overlays.

4.5 DERA HMD/VCS Research & Development Facilities

Notwithstanding the advantages of the HMD it is recognised that the lateral field of view is somewhat less than that available to a person employing direct vision. Research suggests [5] that there is an optimum value of lateral field of view beyond which piloting performance does not significantly increase. Present generation HMDs offer less than this optimum field of view. Within the DERA a major research and development (R&D) programme is being run to investigate and quantify the advantages and disadvantages of a VCS when used for piloting and targeting purposes, and that programme includes field of view research.

The DERA are using two simulators and a modified Lynx aircraft for VCS development. The two simulators are termed HOVERS (at DRA Farnborough) and AFS (at DRA Bedford), some of the results from which lead into the development of the Lynx helicopter itself (based at DTEO Boscombe Down): they provide the means both for carrying out rapid assessments of new concepts and for investigating safety issues prior to actual flight.

HOVERS (**H**elicopter **O**perational **V**isual **E**ngagement **R**ealtime **S**imulation) enables the fixed-base real-time simulation of operational missions. A HOVERS tandem helicopter configuration is shown in figure 5. HOVERS was recently extended to enable one of the pilots to use a HMD, which gave the first opportunity to programme and use the DRA's rotary wing symbology set [5]. The primary advantage offered by HOVERS to the Lynx development is that trade-offs associated with the HMD piloting symbology set may be identified in a mission environment and on an identical HMD to that used in the Lynx.

The AFS (Advanced Flight Simulator) provides an adaptable, safe and controlled environment for the simulation of all types of man-in-the-loop vehicle, and its facilities include the largest motion-cueing system in Europe. This five axis simulator gives realistic motion in surge or sway, heave, roll, pitch and yaw, together with high fidelity visual representation of the outside scene. For VCS research purposes it can be configured with Lynx helicopter controls and set up to handle like a Lynx. It contains the same type of HMD and Head Tracking System as are in the real helicopter.

The DRA modified Lynx (figure 6) has a modified nose which houses the steerable platform and infra-red sensor. The cockpit is configured for a safety pilot on the right,

supplied with standard flight instruments, with the VCS pilot flying the aircraft from the left seat, and his main information source is the HMD.

The need for a safety pilot is crucial because the bulk of the test flying is flown at low and very low levels, typically 50 to 100ft. The HMD is driven mostly from avionic systems separate from those supplying information to the safety pilot, in order to maintain the integrity of the safety pilot's information. The nose mounted turreted platform may be steered to +/- 120° in azimuth and +30/-90° in elevation. Its maximum rate of movement is 110°/s and acceleration 1000°/s^2: both values are considerably less than can be achieved by the human head but the platform is nevertheless sufficiently responsive not to cause undue man/machine interface problems. The thermal imager output is fed to the HMD and drawn on a HMD of display extent 48 degrees in azimuth by 36 degrees vertically. The HMD is fully overlapped, that is, the pictures displayed to the left and right optics are identical. (Most other HMDs which provide a large total field of view do so by providing left and right displays which are only partially overlapped). The HMD used on the Lynx is shown in figure 7. The design originally accommodated image intensifier tubes on both sides of the HMD, the outputs from which were optically injected into the combiner glasses. This facility is not used in the present VCS trials. A symbol generator enables selected mission and piloting information to be displayed, mixed with the thermal imaging video. As mentioned earlier (para 4.4), data fusion of the outside world - the fusing of the best aspects of Thermal and Image Intensifier (II) imagery - is another important research issue. It is often complicated by the separation of the sensors, eg. nose and rotor mast turret. The pilots eye position may be 6ft from the nose and 4ft from the mast and parallax corrections must be incorporated in order to present to the crew a "true" picture of the outside world. Research continues into the problems with pilots using HMD, such as turning too early and ensuring adequate rotor tip clearance when manoeuvring into confined areas; hopefully this work will lead to the development of collision avoidance and tip proximity awareness systems.

4.6 Test & Evaluation Clearance Issues

To date the information provided by HUD displays has been regarded as advisory. However, the use of a HMD is radically different to a HUD, because of the compulsive nature of the information which the pilot views constantly and because the real world view may be artificially enhanced. With such displays it is very easy for the pilot to become dis-orientated when presented with conflicting or incorrect information. Failure cases and the failure cues provided to the pilot must also be carefully assessed. A HMD is thus a primary flight instrument, and all the drivers to it are flight critical. This makes it essential that an HMD is not evaluated in isolation but within the overall system evaluation, as it is only at a system level that problems may be apparent. For example, as a result of latency, HMD and real world cues may not correspond, causing dis-orientation.

It is clear that HMDs require assessment against appropriate mission based criteria and cannot be assessed in isolation - which leads us back to the ADS-33 philosophy. In particular a HMD will contribute significantly to the UCE, and it is probably only within such a concept that the information which is presented to the pilot can be assessed.

In the interim period before the first UK Apache arrives for testing at Boscombe Down methods have to be devised which will ensure that any HMD is fully evaluated. At present no assessment of a HMD has been made, and it is important that the issue is tackled now before a clearance is asked for. As a minimum, the HMD must be shown to be safe, accurate, reliable and usable. Simulation will certainly play an important part in developing the necessary methodologies. The precise nature of the evaluation undertaken by Boscombe Down will depend upon the division of responsibilities between the contractor and test agencies, but a clear understanding of the requirements to be met must be defined.

In the context of a mission performance evaluation all of the information displayed must be evaluated against its utility for the mission segment in question - it must buy its way onto the display. There is also the contradictory requirement for information to be placed where it is clearly visible, but the centre of the display must clearly be uncluttered. Mission evaluation goes much further than this, however, as a visually coupled system can only be comprehensively tested if a mission can be broken down into mission task elements which may be flown in a repeatable manner. The ability of the pilot to carry these out using the system must then be assessed and any deficiencies isolated as handling qualities or piloting cue deficiencies. An important part of carrying this task out successfully will depend upon a clear understanding of what the precise role is, understanding the systems which are integrated together to provide information to the HMD and the information priorities within the mission task elements. The most important part of the testing is to determine 'cliffs' where handling qualities degrade rapidly as a result of the cues becoming insufficient.

The clearance of systems which enhance the cues available to a pilot in night and poor weather conditions presents a practical problem, in that in order to evaluate the system the aircraft may have to be placed in situations in which the safety pilot - using NVGs say - may wish to take control or make inputs because of the limited cues available to him. This again suggests the need for extensive use of telemetry and real time flight path monitoring.

Other issues which both the R&D and T&E communities need to work closely together on include the HMD equipment itself, this needs to be comfortable for prolonged use by the wearer, and not increase the chance of injury or restrict escape in the event of a crash. The display must be clearly legible in all lighting conditions. Because the crew, especially the pilot, will be essentially flying "head-up, eyes-out", system malfunction warnings will have to be auditory rather than visual; the multitude of warnings must be clear, unambiguous, and when necessary, correctly prioritised. This is especially so when flying in the Night Vision Goggle (NVG) environment where the pilot is required to be "eyes-out" for the maximum amount of time.

5. CONCLUDING REMARKS

The paper has attempted to present some thoughts on near term helicopter technologies that could impact the Uk's new attack helicopter, the WAH-64 Apache. In the near future the adoption of a synergistic capability for self protection of the attack helicopter by means of a Defensive Aids Suite and, the introduction of an Integrated Helmet, utilising the latest imagery and data fusion techniques, will enable pilots and mission commanders to operate effectively on the digital battlefield of tomorrow.

The UK's plans to integrate a Defensive Aids Suite and an Integrated Helmet into the WAH-64 Apache's already formidable weapons system should ensure that the British Army fields an attack helicopter at the end of this decade which will dominate the battlefield for the foreseeable future.

DTEO Boscombe Down believe there is potential to subject UK Apache to an ADS-33 handling qualities evaluation to quantify the aircraft's handling qualities and thus identify any potential shortfalls. UK Apache is intended to operate for the first 30 years of the 21st century and an ADS-33 type evaluation will identify and quantify the aircraft's capabilities against a number of mission profiles. This will establish its fitness for the role as well as forming a baseline against which requirements for future improvements can be identified and developed in the most cost effective manner.

Before the first UK Apache arrives at Boscombe Down for testing DERA - the Defence Evaluation & Research Agency (that is DTEO Boscombe Down in partnership with our colleagues in the Defence Research Agency), must develop the required clearance methodologies to test and evaluate the aircraft as

a complete weapons system. Work to develop the necessary test methods has already started. Finally, clearance testing will, undoubtably, make greater use of simulation and place greater emphasis on joint testing with Industry.

References:

1 J Wickes, "Electro-Optical Systems in Platform Self-Protection", UK Journal of Defence Science, January 1996, Unpublished.

2 A Sutherland, "An Initial Consideration of DAS for FOA", December 1994, Unpublished.

3 G D Padfield, M T Charlton, Maj T Mace and Maj R Morton, "Flying Qualities Evaluation of the UK Attack Helicopter Contenders using the ADS-33 Methodology - Clinical Criteria & Piloted Simulation Trials", presented at the 21st European Rotorcraft Forum, Saint Petersburg, Russia, September 1995.

4 Anon, "Handling Qualities Requirements for Military Rotorcraft, Aeronautical Design Standard ADS-33D", August 1994.

5 K L Edwards, "The Development of a Helicopter Visually-Coupled System Research Facility", UK Journal of Defence Science, January 1996, Unpublished.

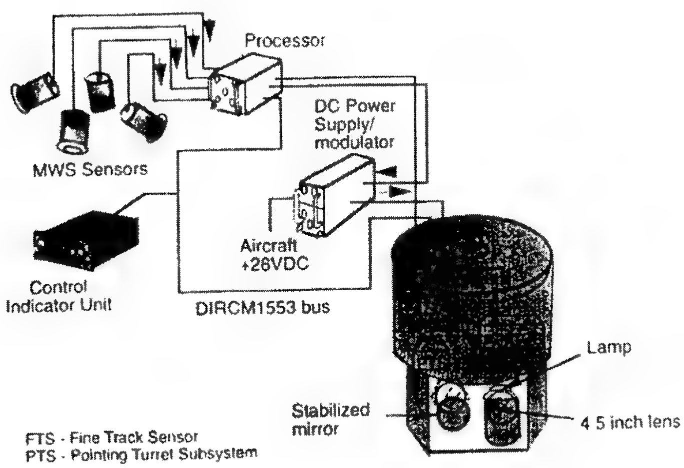


Fig 1 Electro-optical jammer DIRCM

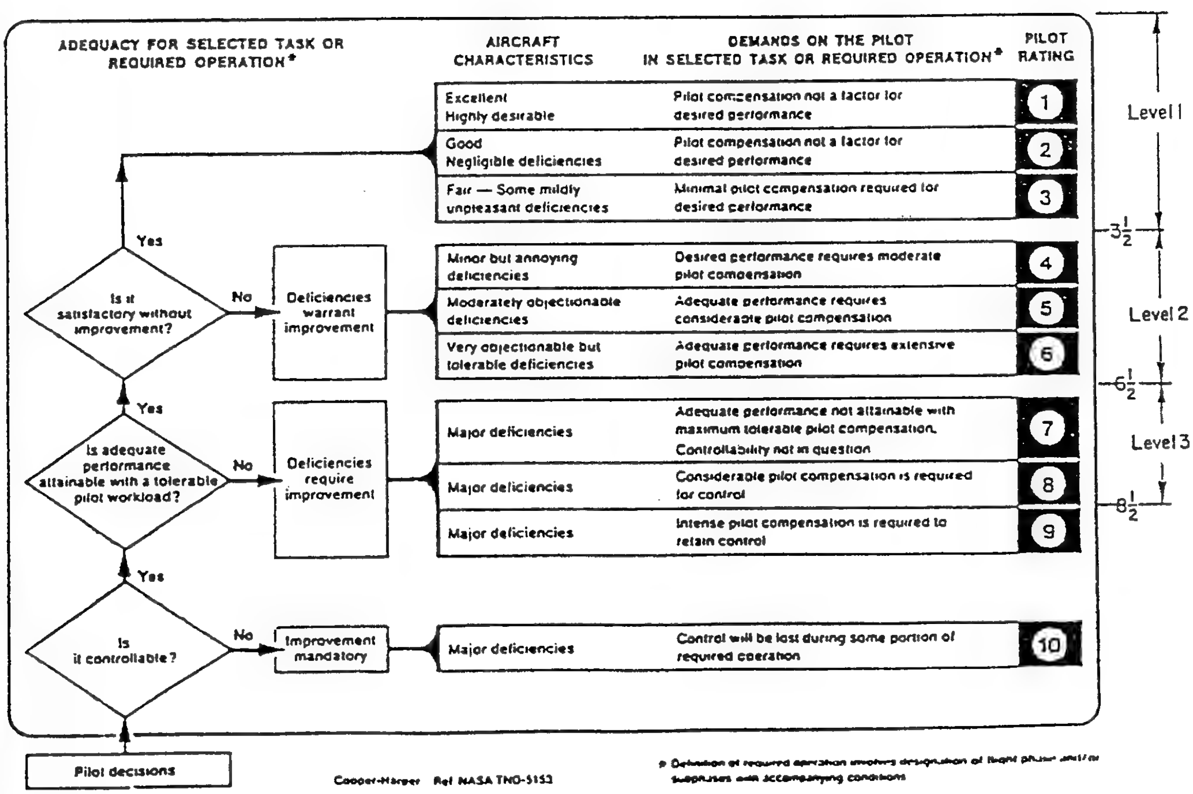


Fig 2 Definition of handling qualities levels

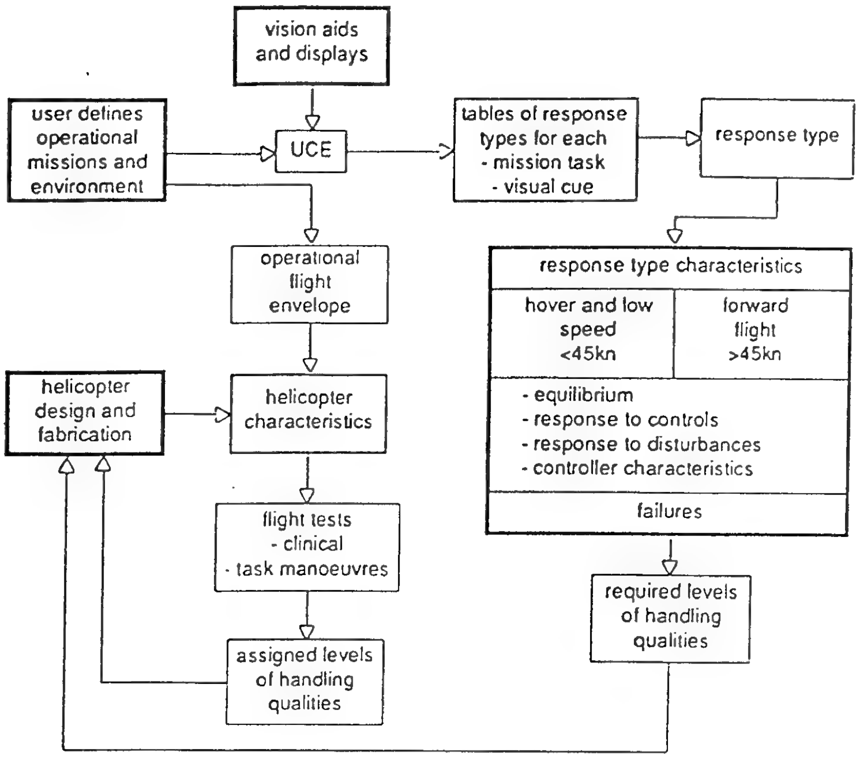


Fig 3 ADS-33 requirements capture, design & evaluation methodology

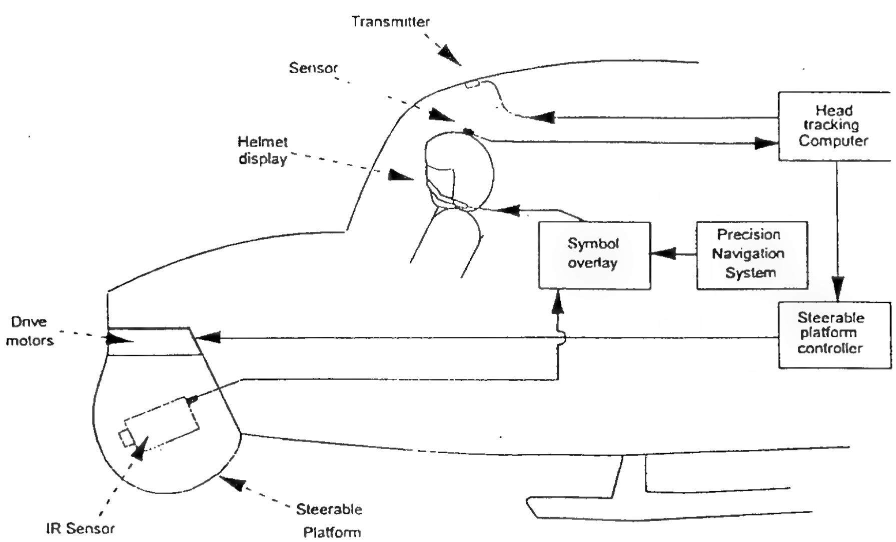


Fig 4 Visually-coupled system block diagram

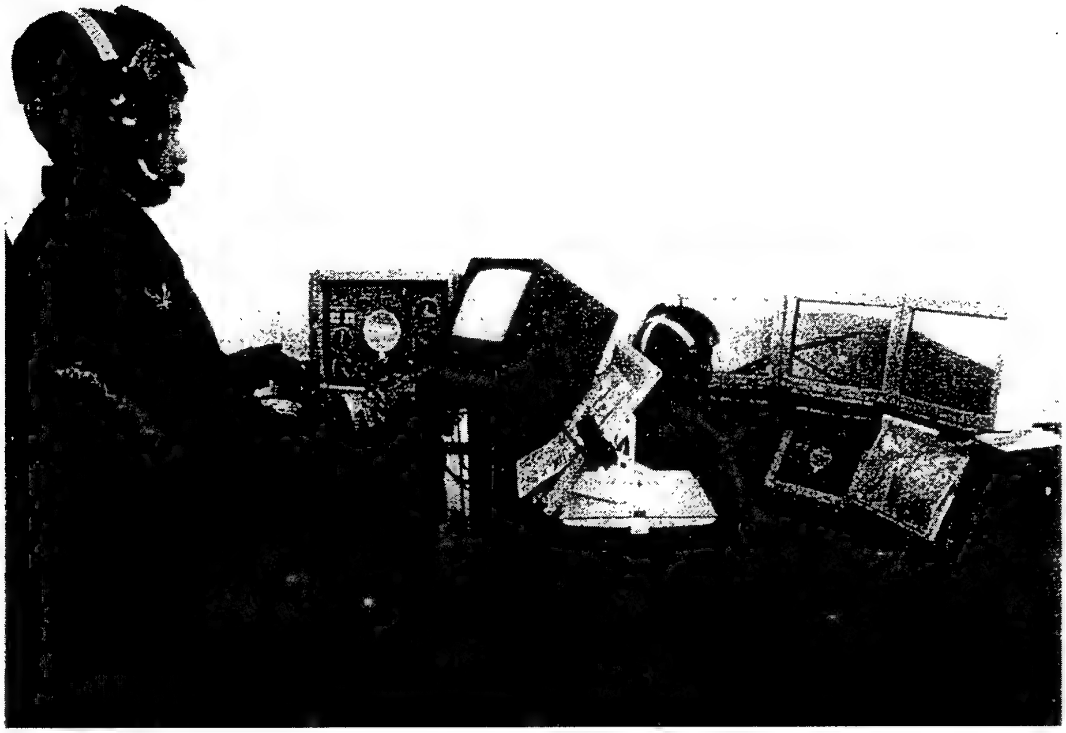


Fig 5 HOVERS Simulator

Fig 6 Lynx flight test vehicle

Fig 7 Lynx and simulator HMD

A Data Acquisition System for the RNLAF MLU F-16 Requirements and Proposal

Lt.-Col. H.J. Koolstra
Royal Netherlands Air Force, 323 SQN
P.O. box 21050
8900 JB Leeuwarden, The Netherlands
Ing. P.M.N. Hollestelle
Ing. J.M. Klijn
National Aerospace Laboratory NLR
P.O. box 90502
1006 BM Amsterdam, The Netherlands

1. SUMMARY

In 1983 the Royal Netherlands Air Force (RNLAF) requested the National Aerospace Laboratory NLR to design, procure and install a flight test data acquisition system to be used with the F-16 fighter aircraft. The design was heavily based on the systems, which were at that time nearing their completion for flight tests with Fokker aircraft. The system was delivered to the RNLAF in 1984 and has been continuously in use since that time.

With the coming introduction of the Mid-Life Update programme of the F-16, it was foreseen that the current system would not be able to fulfil its tasks anymore. The RNLAF together with NLR draw up the requirements for a new data acquisition system. A proposal for the new system was made by NLR, again based on recent developments of flight test instrumentation for Fokker aircraft, but also with future developments in the field of airborne flight test instrumentation in mind.

In this paper the requirements for the new system will be given. The proposed system will be described by means of a general concept. Although the final implementation of this general concept is not decided upon yet, the benefits and drawbacks of a possible implementation, based on the Common Airborne Instrumentation System standards, are discussed. It is concluded that there is a preference for this implementation, provided the tight time schedule can be met.

2. INTRODUCTION

In 1983 the Royal Netherlands Air Force (RNLAF) awarded a contract to the Netherlands National Aerospace Laboratory (NLR) to design, build and install a data acquisition system in one of their F-16 aircraft. The system had to be used for two types of flights, namely operational flights and flights with a technical objective. The first type consists mainly of flights for mission training where recording of data may improve tactics and trials to determine or improve the quality of a system. The second type consists of flights mainly related to a special programme, e.g. certification of new stores or technical evaluation of new or modified aircraft systems.

In October 1984 the instrumentation was installed in a single seater F-16A aircraft. Shortly hereafter a two seater F-16B aircraft was modified to allow the installation of the instrumentation package in this aircraft as well. Because in the course of the flight tests the RNLAF preferred to have an additional two seater over a single seater, it was decided in 1987 to bring the F-16A aircraft back to standard and modify a second F-16B instead. Up till now the instrumentation package has performed to its specification. Moreover NLR has successfully used similar systems to support flight test programmes of their other customers.

In the time span from the beginning of 1998 until 2000 all the aircraft of the RNLAF will be modified on behalf of the Mid-Life Update (MLU) programme. After the modification programme the aircraft are expected to be operational until 2020. Since the avionics of the MLU F-16 is extended significantly, for instance resulting in four instead of one Mil-Std-1553 buses, it became clear that a new instrumentation package will be necessary. For that reason the RNLAF asked NLR to propose for such a new instrumentation package. Besides specifying new functional requirements also attention was paid to improve the operational performance of the system.
In the next sections both functional and operational requirements are discussed. Additionally the proposed

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

system meeting these requirements is described in some detail. Because the new system is based on long term experiences with the present system, a short description of the present system will be given as a start.

3. PRESENT SYSTEM

The starting points for the development of the present system were:

- The system should have the potential to be used for the various flight test programmes with minor modifications.
- It was required that reconfiguration of the aircraft from test status to operational status could be done in a very short time (less than 24 hours).
- The permanent structural modifications to the aircraft should be as limited as possible.

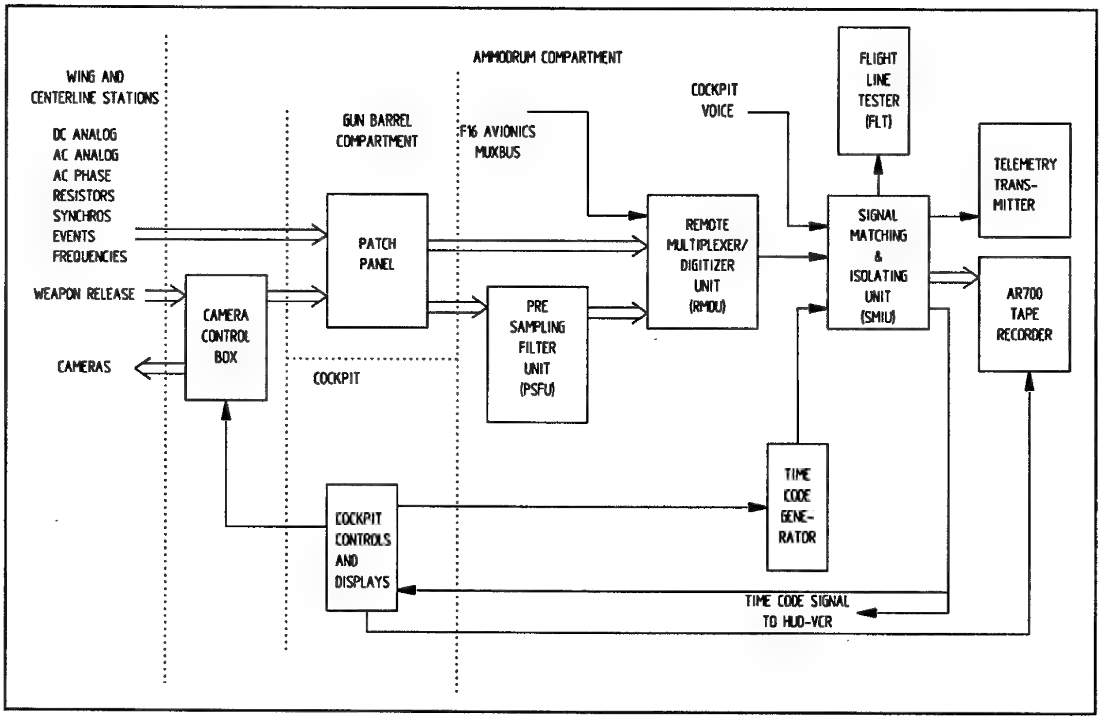


Figure 1: Block diagram of the present F-16 instrumentation.

The resulting system is depicted in figure 1. The data acquisition system, mainly consisting of a signal conditioning unit, a multiplexing and digitising unit and an airborne digital data recorder, is located in a dedicated instrumentation rack, mounted in the ammodrum compartment. The various analog and digital input signals are connected to the data acquisition unit via a patch panel, mounted in the gun barrel compartment. From there a standard wiring harness is routed to nine wing and centreline stations. At these stations the transducers required for a specific flight test programme can be installed. This concept allows for a relatively easy reconfiguration of the instrumentation system to the needs of a flight test programme. The camera system, mainly used to record the separation trajectory of a store, consists of up to five independently operable high speed film cameras. This system makes use of the same wiring harness as the data acquisition system.

The data acquisition and camera system can be controlled from both the forward and aft cockpit by means of additional control units.

For installation of the instrumentation the ammodrum and gun have to be removed from the aircraft. The permanent modifications to the aircraft are mainly:

- installation of the instrumentation wiring harness to the remote stations;
- installation of wiring to the cockpit;
- mounting points for the instrumentation package;
- modifications to the Electronics Cooling System, providing adequate cooling of the instrumentation.

A more detailed description of the present instrumentation can be found in Ref. 1.

4. REQUIREMENTS

4.1 Functional requirements

For the new system at least the same functional requirements as for the present system apply, which will not be repeated in this paper. However, since the avionics of the MLU F-16 are extended significantly, the instrumentation has to be extended too. The main items are:

- The system has to provide input capacity for four dual redundant Mil-Std-1553 multiplexer buses and the F-16 weapon data bus. Selections of data to record from these buses have to be made, however for possible future avionics flight testing, it must be possible to upgrade the system for recording of complete data buses.
- The throughput rate of the present system is 1.5 Mbit/s, which occasionally has been used. The increase of required parameters from the multiplexer buses will demand for systems with a significant higher throughput rate. It is estimated that for the new system a maximum throughput rate of at least 5 Mbit/s is required.
- Since the number of video sources is increased, i.e. by use of Multi Function Displays (MFD's), targeting and navigation pods and TV guided missiles, provisions have to be made to record the various video signals.

An important addition compared to the present system is the requirement to have a display in the cockpit on which in-flight selectable sets of at least four parameters in engineering units and in numeric format can be displayed.

4.2 Operational requirements

Most of the operational requirements are based on the twelve years operational experience with the present F-16 instrumentation. In general there is a strong requirement to limit the degradation of the aircraft from its operational status as much as possible. Preferably the aircraft has to be fully operational with all the instrumentation installed. This means:

- No removal of gun and/or ammodrum required for installation of instrumentation. Moreover it even must be possible to use the gun while instrumentation is installed.
- No additional cooling requirements for the instrumentation which would make adaptation of the aircraft ECS necessary.
- The additional flight test wiring has to be limited as much as possible.
- No adaptations to the cockpit lay-out for instrumentation control and display of selected parameters. For this purpose it is preferred to make use of the Multi Function Display (MFD), already present at both the forward and aft cockpit.

In addition the following requirements apply:

- In the present data acquisition system the sampling sequence is stored in Erasable Programmable Read Only Memory (EPROM). If changes in the sampling sequence are required, the data acquisition unit has to be accessed to replace the EPROM. For the new system the sampling sequence shall be externally programmable by means of a data link.
- Because of reduction of time required for processing of film and maintenance of equipment, it is preferred to replace the present film cameras by high speed video cameras.

4.3 Other requirements

Although an optimised system from a technical point of view is preferred, also requirements related to the time schedule can influence choices in the realisation of the instrumentation system. The first flight tests with the MLU F-16 are foreseen in the middle of 1998. One of the first dual seaters which are modified will be allocated to be instrumentated. This aircraft is expected to become available for installation of the instrumentation in January 1998. The instrumentation has to be operational before June 1998.

5. PROPOSED SYSTEM

5.1 General concept

Free from equipment limitations the requirements can be translated into a general concept. Figure 2 shows the general concept of the proposed data acquisition system.

A Central Controller (CC), which will be mounted in the aft avionics compartment, acquires all data and distributes these data to a recorder, a telemetry system and a cockpit display unit. The signals locally available at the aft avionics compartment, such as the Mil-Std-1553 buses, weapon bus and a part of the analog and digital signals, tapped from the Flight Loads Recorder (FLR) inputs, are connected directly to the CC. The CC takes care of conditioning, multiplexing and digitising these signals.

Analog and digital signals at remote locations, i.e. the wing and centreline stations, are acquired by miniature Remote Data Acquisition Units (RDAU). These units are able to condition, multiplex and digitise the signals to be measured. They also provide transducer excitation voltages if necessary. The RDAU's are connected via an instrumentation bus to the CC. Via this bus the CC is able to set up the RDAU measurement channels, e.g. amplifier gain and presample filter cut-off frequency, and acquire the digitised values.

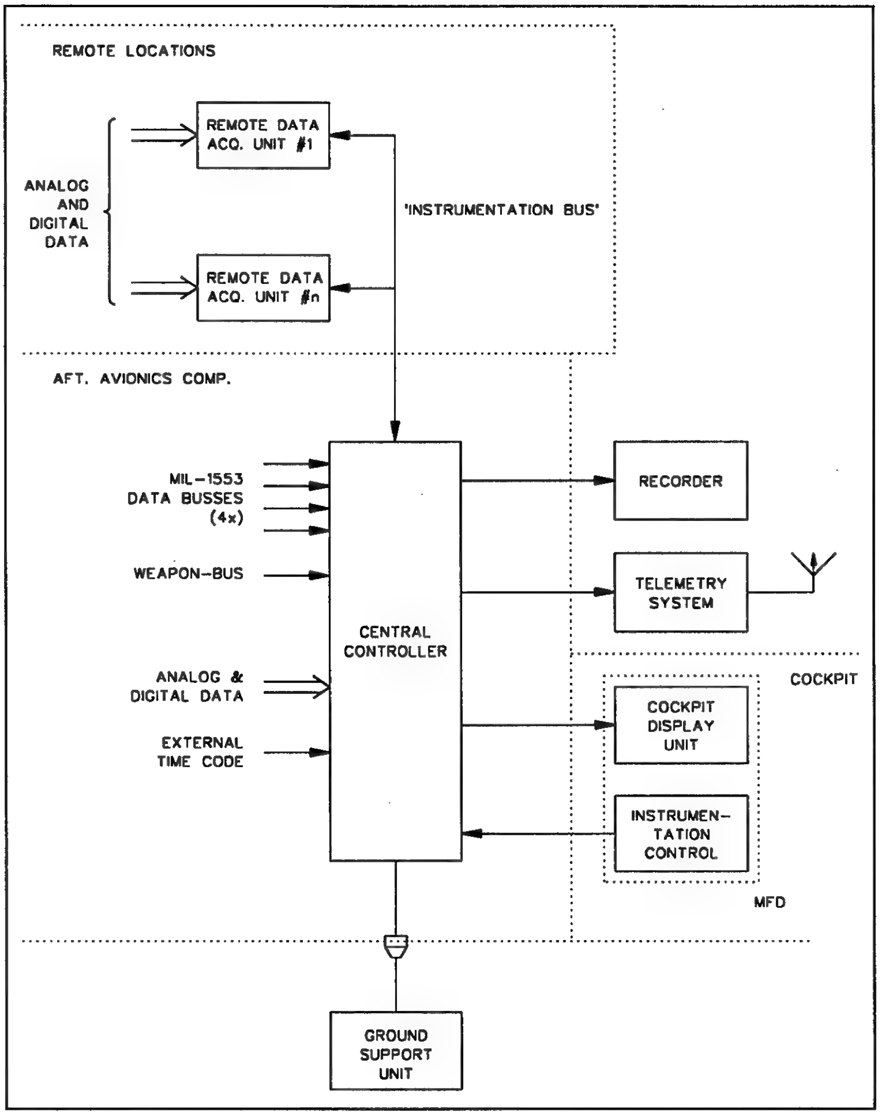


Figure 2: The general concept of the proposed data acquisition system.

In this concept the film cameras or future high speed video cameras can also be considered as a RDAU, receiving control commands and sending status information via the instrumentation bus.

The CC accepts an external time code signal, e.g. from a Global Positioning System (GPS) receiver, to synchronise its internal time code generator. This synchronised time code data will be available at the data outputs to recorder, telemetry system and cockpit display unit.

The formats of the CC output data streams to recorder, telemetry system and cockpit display are downloaded to the CC from a Ground Support Unit (GSU). With this GSU also data can be displayed for check-out and maintenance purposes. The data formats can be configured independently, for example all required data to the recorder and a subset of these data to the telemetry system.

The Cockpit Display Unit (CDU) will be able to display in-flight selectable sets of at least four parameters in engineering units at both the forward and aft cockpit. To meet the requirement not to change the cockpit lay-out, use can be made of one of the aircraft's MFD's. The switches of the MFD can be used to control the instrumentation.

5.2 Implementation

Experiences, gained with designing, building and operating large data acquisition systems for flight tests with Fokker prototype aircraft, learned that the described general concept can very well be realised with

the Programmable Conditioner Unit (PCU) or the Programmable Master Unit as the central controller. Both units are manufactured by Aydin Vector Division and make use of the Aydin Vector proprietary instrumentation bus, the so called 10-Wire Interface (10-WIF), to communicate with the RDAU's. Because of its small size the Micro Miniature Signal Conditioner (MMSC) will be a suitable solution for these RDAU's.

However new developments in electronics tend towards creating systems based on an open bus architecture, which are expandable by several suppliers. In the field of airborne flight test instrumentation, equipment meeting the standards of the Common Airborne Instrumentation System (CAIS) is under development since March 1991 (Ref. 2). The CAIS standard is being developed by the United States Department of Defence (US DoD) to promote standardisation, commonality and interoperability among aircraft test instrumentation. By US public law of November 1991 all developments regarding airborne instrumentation system for US Army, Air Force and Navy have to be based on the CAIS standards. The F-22 and F-18 flight test programmes are the first users of CAIS (Ref. 3).

There are strong arguments to base the instrumentation of the MLU F-16 on the CAIS standard too:

- Commonality: because it is expected that many manufacturers of flight test equipment will develop equipment meeting the CAIS standard, the procurement is not restricted to one supplier.
- Modular, expandable open architecture: this provides the capability to expand the system to meet flight test programme requirements, upgrade system

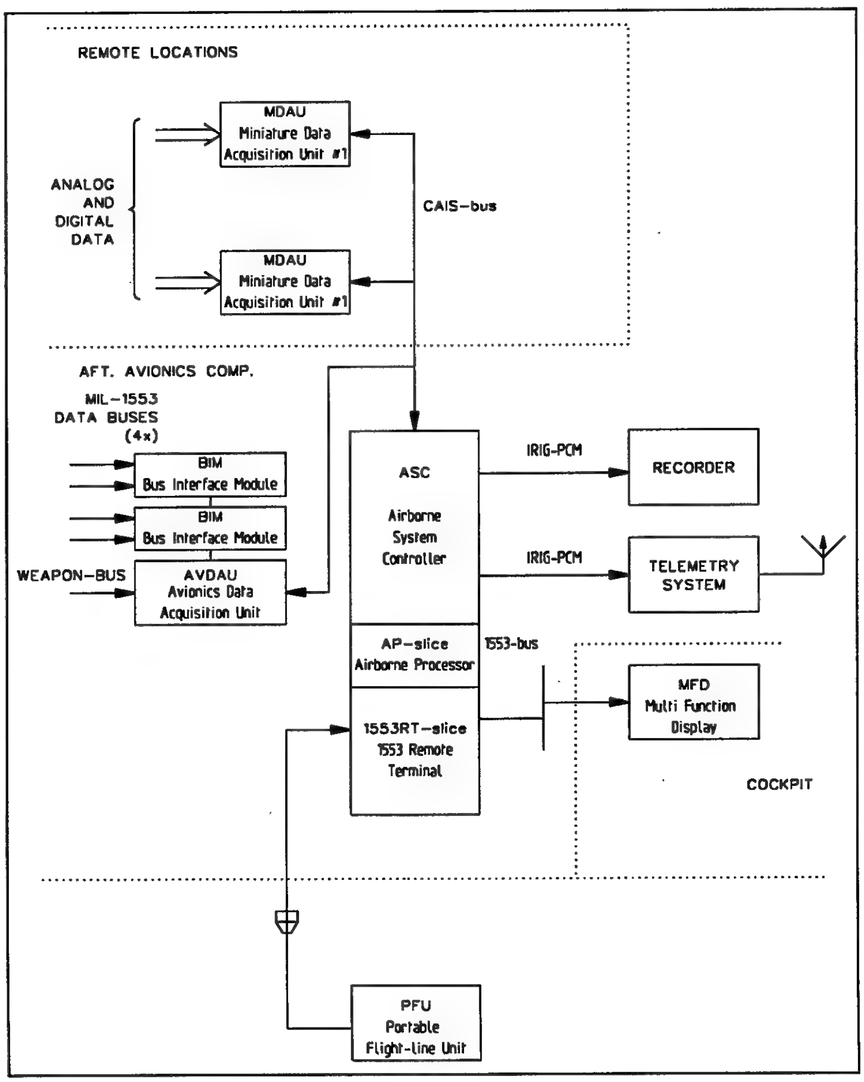


Figure 3: CAIS implementation of the proposed system.

components with new technologies, and meet emerging technical requirements. More data acquisition capacity can be added to an existing instrumentation installation without redesigning, removing and reinstalling a completely new system.

Figure 3 shows the CAIS implementation of the data acquisition system. The Airborne System Controller (ASC) takes a central place in the system. It takes care of controlling the CAIS instrumentation buses (up to three) and of formatting and distributing the acquired data. The maximum data output rate is 24 Mbit/s, which allows for future system expansion, for example with monitoring of the complete Mil-Std-1553 bus data.

The ASC is extended with two 'slices': the Airborne Processor (AP) slice and the 1553 Remote Terminal (1553RT) slice. The AP processes the data to engineering units. The 1553RT is intended to communicate with the MFD for instrumentation control and display purposes.

The acquisition of data from the aircraft avionics buses is performed by the Avionics Data Acquisition Unit (AVDAU), extended with two Bus Interface Modules (BIM). The acquisition of other digital and analog data is performed by the Miniature Data Acquisition Unit (MDAU).

The Portable Flight-line Unit (PFU) is based on a Personal Computer (PC) and providing capability to generate and load data formats; load, modify and verify the memory contents of the airborne units; execute initiated built-in test; verify airborne system configuration; and display/record the results of all significant operations.

In the present F-16 instrumentation good results are obtained using the Merlin PCM to Video Encoder ME-981 and a TEAC Hi-8 airborne video recorder. Maximum input rate of this system is 2.2 Mbit/s but upgrades to 5 Mbit/s are available now. Because ground station facilities are based on this equipment too, it is preferred to leave this part of the system unchanged.

6. CONCLUSIONS

At this stage final decisions about the implementation of the instrumentation are not made. In the described CAIS implementation several problems still have to be solved in more detail. The main problem areas are:

- How can the cameras be controlled as a remote unit connected to the CAIS-bus?
- How can the AP and 1553RT be programmed to communicate with the existing MFD's for parameter display and instrumentation control?

Besides technical problems, the requirement to have the instrumentated MLU F-16 ready for flight tests before June 1998 can be an important reason to fall back on well known and proven techniques and equipment. On short terms the availability of equipment meeting the CAIS standards have to be investigated and an assessment has to be made how much time and money for familiarisation will be necessary.

The present F-16 system has supported the flight test programmes of the RNLAF for more than twelve years. Similar systems were used in flight test programmes for other customers of NLR. If we will be able to deal with the problems above, in 1998 there will be a system installed in the MLU F-16 aircraft, very well capable of supporting flight test programmes for at least another decade.

7. REFERENCES

1. Storm van Leeuwen, S., "A Small, Flexible and Powerful Data Acquisition System For The F-16 Aircraft", NLR MP 85074 U, 1985.

2. Faulstich, R.J., "Common Airborne Instrumentation System", paper presented at the 22nd Annual SFTE Conference, St. Louis, MO, Aug. 1991.

3. Hochner, B., "CAIS for the F-22", AIAA-94-2130-CP, 1994.

BALANCING MODELING & SIMULATION WITH FLIGHT TEST IN MILITARY AIRCRAFT DEVELOPMENT

William J. Norton
Major, USAF
Arnold Engineering Development Center
AEDC/DOM, 1099 Avenue C Suite 113
Arnold AFB, TN, 37389, USA

1.0 SUMMARY

The use of modeling and simulation (M&S) in the development of aerospace vehicles has evolved in step with the associated analytical and computational tools. During this evolution M&S has been balanced with necessary levels of flight testing as an integral part of the development process. Now, program managers are being urged to seek dramatic reductions in flight testing and to compensate with much greater reliance on M&S. A strong emphasis on fostering M&S development is essential to extend the aerospace state-of-the-art, and does hold promise for reducing development cost and cycle time. However, recent test programs do not provide confidence that M&S tools are presently of sufficient accuracy to permit a preponderant reliance on them at the expense of flight test. Premature dependency will introduce the risk that the system deficiencies usually found in flight testing will go undiscovered until after the vehicle is in production and operation. However, a concerted effort to research and correct demonstrated M&S failures to predict certain system characteristics will, given time, allow a complementary reduction in flight testing. This would allow the shifting balance of M&S with flight testing to be managed so as to keep program risks acceptable and ensure the high quality of resulting weapons systems.

2.0 INTRODUCTION

Much of the air vehicle development process prior to flight testing relies on indispensable analytical predictive tools and ground testing. The first flight of a new aircraft is preceded by years and hundreds of millions of dollars of mathematical modeling (aerodynamics, control systems, engine decks, etc.), simulations (pilot-in-the-loop flying qualities simulators, flight dynamics, avionics integration, etc.) and ground tests (wind tunnels, hardware-in-the-loop avionics labs, engine static tests, etc.). These will be collectively referred to as modeling and simulation for the purpose of this paper. The M&S tools incorporate artificial flight conditions, simplified system models, empirical factors, proprietary corrections, and engineering assumptions. All of these elements have inherent uncertainties and tolerances, and the resulting information is filtered with the application of engineering judgment and experience. These uncertainties make flight testing an essential element of aircraft development, providing the final proof of the design and the data necessary to validate and verify (V&V) the models and simulations. However, flight testing has its own limitations, including fewer measurements, poor statistical relevance, limited repeatability, and simulated operations. Measurements also have tolerances and uncertainties. So, each approach plays a vital role in the development of a sound system. This process is shown in Figure 1. The figure illustrates that development does not end when flight testing begins, but that flight testing is but a continuation of development.

The changing nature of military air vehicles (e.g., greater flight dynamic conditions, more electronic-intensive systems, requirement for more accurate weapon delivery, more demand for safety, etc.) has driven the need for more detailed and thus longer, more expensive flight test programs. Disappointing combat results and greater weapon system costs have also been behind the need for more comprehensive testing. The rising expense of the vehicles generate greater scrutiny of development efforts by elected leaders and the public. None of these factors appear likely to change in the near future. Now, changes in the acquisition process are aimed at reducing the cost of weapons while accelerating development and deployment. Consequently, initiatives have been undertaken to reduce flight test program duration and costs by testing smarter. Part of these initiatives is to move from what is perceived as flight testing consisting mostly of an inefficient *fly-fix-fly* methodology to a *predict-test-compare* approach with increased reliance on M&S. However, policy-makers also see the possibility of reaping tremendous time and cost savings by dramatic reductions in flight testing.

The fundamental purpose of testing in military air vehicle development is to verify that the system performs as required and to ensure operator safety. This process has come to include detailed, costly, often lengthy, and sometimes hazardous flight testing as the final proof of the design or to collect data required to correct deficiencies. Flight testing provides vital system performance and integration data while consistently revealing all manner of design shortcomings or unexpected characteristics not predicted through ground testing or analysis. Even with the advances in analytical tools, design flaws, some of them dangerous, are consistently revealed in flight testing and sometimes later in training or combat. In fact, every major military aircraft development program since World War II has had significant design deficiencies uncovered through flight testing. Fifty years of post-war military

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

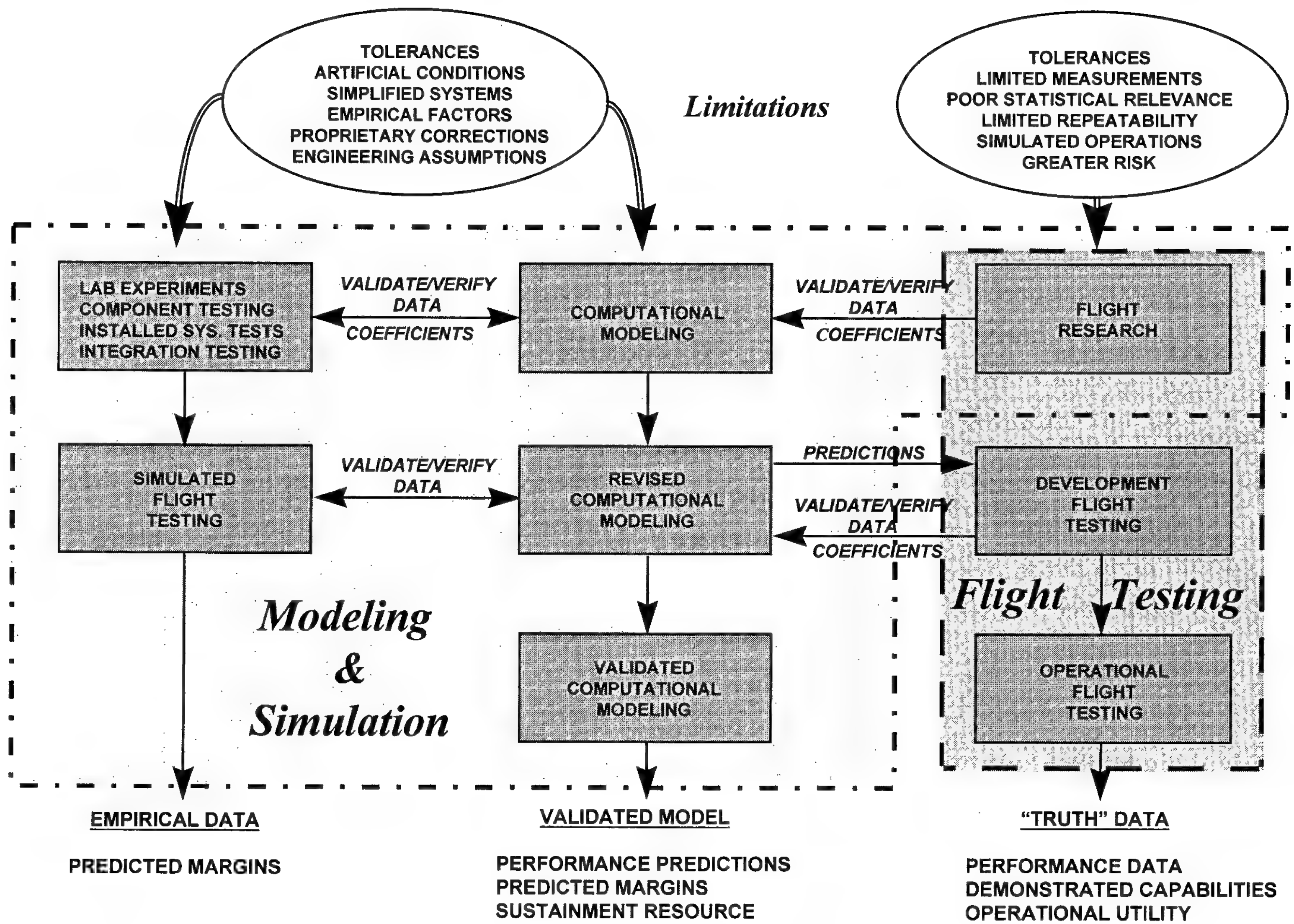


Figure 1 Contributions of Modeling & Simulation and Flight Testing to the Development Process

aircraft development has demonstrated that significant system problems will arise during flight testing (see Tables I through V for examples, numbers in parenthesis following the program title is the year of the first flight) and should be considered a natural part of developing highly integrated and dynamic warplanes. This is especially true with each generation of weapon system pushing the state-of-the-art and introducing new unknowns or uncertainties into the designs. Also, despite the extent of flight testing, weapons have still had problems revealed later in fleet operations (see Table VI for examples). Hence, it is difficult to conclude that the present flight test practices result in over-testing. Even the most recent development projects (Tables III through V) have demonstrated that M&S is not sufficiently accurate at present to support dramatic reductions in flight testing, and no clear reduction is evident in a survey of flight test programs over the last 30 years (Table VII).

Certainly, M&S provides the correct answer far more often than the wrong answer. But, it is a mistake to expect such an extremely complex system as a modern warplane to work perfectly the first time in all aspects of its design. Regardless of this, our leadership has made it clear that development programs are not getting as close to this ideal as they would expect. Many years of research and testing may be required to achieve the M&S accuracy necessary to substantially reduce the number and severity of design deficiencies being built into prototype articles. This is an essential step in contributing to a large decrease in the extent of flight testing and the resources it requires. Reducing flight testing without a balancing increase in M&S reliability would only inject greater risk into the development process. The end users of the systems would have to assume most of this risk in accepting aircraft of uncertain capabilities and safety. Any substantial reduction in flight testing will risk allowing more deficiencies to go undiscovered as the system enters production and is fielded.

3.0 WHY REDUCE FLIGHT TESTING?

There are six statements which have been promulgated by weapon system developers and acquisition leaders as reasons for seeking to reduce flight testing. Each of these points could be addressed in separate articles, so only brief comments will be made in examination of them. They reveal a general frustration with flight testing, but not necessarily an appreciation of the valuable role played by this work.

1. *Flight testing costs too much.*
Flight test activities are markedly more costly than other development activities, obviously because of test range and aircraft operating expenses. However, manpower is usually the greatest expense in open-air testing, as is common with earlier program work. A reduction in the use of range resources, aircraft operating hours, and associated labor, would certainly reduce program costs. However, the use of these resources are largely dictated by the nature of the system, the length of the program as determined by the methods to be used, and especially the unexpected results found during testing. Any reduction in flight testing must be weighed against the greater costs of correcting production articles for design deficiencies revealed in later fleet operations.

2. *Flight testing takes too long.*
Experience has shown that the time required to resolve the design deficiencies uncovered during testing is usually the pacing factor in the length of a test program. Another principle problem is that test program schedules have almost always been optimistic. This usually reflects a basic optimism about the design. But, with flight testing coming towards the end of the development cycle, the testers are frequently left to make up for schedule slips and budget overruns which occurred earlier in the program. The delayed C-17 development flight test program was initially planned as a very ambitious 70 aircraft-month effort. Once testing began it quickly became evident that this would simply be unachievable with the types of development problems being encountered, and a revised plan yielded a 135 aircraft-month program. It is difficult to justify building time into a test schedule to allow for slips induced by future problems, but such slips have almost invariably occurred. Greatly accelerating flight testing holds its own risks, including adversely impacting the quality and safety of the work. Follow-on operational testing would have to address the problems overlooked in the initial testing, with this taking on more the characteristics of original development testing. Too many recent flight test programs appear to have been conducted in a crisis mode. The initial flight testing is usually the only chance to collect the invaluable in-flight data used to sustain the system during its life. It is critical that the testing be done properly. Haste generally does not allow for this. Certainly, if fundamental changes are made in how tests are planned, such as deleting safe envelope expansion build-ups, then the amount of testing and the associated time can be substantially reduced. However, the personnel and program risks of such "unlearning" of flight test principles would be unacceptable. The very fast pace of the MD-11 airliner certification flight test program was likely a significant contributor to the problems encountered by commercial operators (Table VIa).

3. *Flight testing attracts high-level scrutiny.*
When an aircraft - years and hundreds of millions of dollars in development - finally begins to show what it can do in a manner clear even to a layman, it is perhaps inevitable that the policy-makers will take a keen interest. The scrutiny is perhaps unavoidable, but the principal problem frequently lies in mistaken perceptions that flight test should be risk-free and fault-free, and design problems should not be found so late in development. It is these misperceptions which must be corrected. The undesirable reactions of senior personnel is exacerbated by the

practice of commencing production before development (including flight testing) has been completed. Under such conditions, problems found in flight testing are problems being built into fleet aircraft. Design flaws found during flight testing in a concurrent development effort will likely have far more profound program impact than for a sequential program.

4. *Flight testing places expensive resources at risk.*
The fundamental objectives of flight testing are to document system performance, and to demonstrate that the system works safely and as expected. Test aircraft *are* expensive, and some of this testing *is* necessarily high risk. However, it is preferable to accept risks taken under controlled test conditions to achieve the fundamental objectives than to accept the possibility that a potentially deadly fault or unacceptable system characteristic will be encountered for the first time in training or combat.

5. *Flight testing reveals too many design deficiencies, some of which are of arguable significance.*
A test that reveals a design deficiency is still a successful test. Developers should be pleased that the fault was found under controlled test conditions instead of in the field where an operator may have been injured or a mission jeopardized. Whether a problem is significant or not is generally a matter of perspective, and the end user should be the final arbiter. The disagreements among a team about which problems deserve detailed investigation and resolution may be uncomfortable, but they are an important means of avoiding group-think and to ensure that all views are heard. Like democracy, team decision making is not always quick and seldom pleases everyone. However, it has been shown to yield the best results.

6. *During flight testing, program control tends to shift to large and domineering test organizations.*
The testing organization performs a service for the development agency. That agency pays the bills and are ultimately responsible for the management of the program. Program managers naturally yield some control to the test organization which is tasked with planning and conducting a test project. The testers have minimal requirements for safety which can seldom be relaxed. However, it is up to the development agency to provide the strength of leadership to direct the program. When a leadership vacuum is sensed, the test personnel will naturally move to fill it as they see necessary for the good of the program.

It is important to note that the six statements presented above do not accuse the test and evaluation (T&E) community of failing to provide warfighters with safe and effective weapon systems. This fact indicates that the process is not broken, it is simply perceived as inefficient or outside the effective control of program managers. In attacking these concerns, the hazard is that process effectiveness will be undermined. Any reduction in flight testing must be balanced against possibly adverse program impact, increased operator risk and potential operational disruptions that would occur in correcting production articles for design deficiencies revealed later in the field. The principle action to correct the perceived problems with flight testing is not necessarily a reduction in flight testing, but rather optimization of the value added to the weapon system and the reduction in program risk achieved by the testing.

Any change in the balance of flight testing with M&S would not change the pressures already facing program managers. Cost and schedule, combined with the usual engineering trade-offs, will still result in compromises being made in the extent and effectiveness of M&S in a program - even if it is intended to largely replace flight testing. An example of how M&S tools can be short-changed to the detriment of the program was revealed in the crash of the YF-22. Despite all of the analytical and simulation tools available to predict the likelihood of pilot-induced oscillations (PIO) - one of the most researched aircraft flight control characteristic in the past ten years - the YF-22 development team decided to forego an adequate investigation of the PIO susceptibility of their design. Subsequent evaluation showed that these tools would have demonstrated that the aircraft was PIO-prone - a factor contributing directly to the crash. Preparing software and computational models, and performing extensive analysis, will also require more time and money as the process becomes more complex and more is demanded of M&S. The development process may be better served by looking to reduce the oversight and reporting requirements which burden the program office and contractor, and which add time and cost to the whole effort.

4.0 BOTH ESSENTIAL ELEMENTS

The aircraft development process has always consisted of a great deal of ground testing and computational analysis. The use of M&S has steadily expanded because of the clear savings in uncovering integration and overall design shortcomings prior to flight testing and commitment to series production. Hence, the expansion in the use of such tools is not necessarily due to any new paradigm, but rather the natural evolution of design tools benefiting from advances in digital computing, mathematics, and research. For example, early aircraft aerodynamic design concept exploration was once performed through wind tunnel testing. But, this is now mostly accomplished through computational modeling, with only the most promising design tested in the tunnel to V&V the analysis. The use of M&S in system integration and avionics development is clearly more efficient than performing these activities in flight, but flight testing remains the venue for the validation and verification of the design work.

An example of successful reliance on M&S in an effort to reduce flight testing can be found in the area of aircraft stores carriage and release certification. Because of the many weapons and carriage configurations which are now

possible on modern fighter-bombers, it is simply impractical to flight test every configuration at every carriage and release condition. This has led to more reliance on M&S to reduce flight testing to only those areas where problems are suspected, where data are required to V&V the analytical models and wind tunnel data, or conditions which could not be satisfactorily simulated. The same approach has been applied to store delivery accuracy. Recent programs have demonstrated that this approach can reap significant savings by a reduction in stores compatibility and bombing accuracy flight testing. These are examples of experience, sound V&V, and evolutionary development leading to a well considered M&S implementation.[1] Another outstanding example is the simulated flight testing of the F-15 radar. This ground test of the installed radar had the jet parked with its nose projecting into an anechoic chamber in which simulated targets were generated under various modeled conditions.[2] The more controlled chamber conditions allowed multiple test cases to be run quickly, isolating areas where flight test substantiation data were required or potential problems needed to be explored. The F-15 ground radar testing gave three times the data at a third of the cost compared with the open air range, although flight testing was still considered essential validation of the results.

The continued expansion of M&S is inevitable and essential, and is worthy of special initiatives and funding. It is virtually certain that M&S holds great promise for accelerating the development process, as envisioned. But, placing too great a reliance on these tools before they have been adequately validated and verified gains little. The V&V process becomes more critical when stretching the state-of-the-art (common with military systems) which perpetuates the uncertainty in the mathematical artifices. Flight testing is still the most truthful and most demonstrable means of verifying system performance.

The importance of actually demonstrating aircraft capabilities should not be understated. Government officials and representatives of operational commands may not be satisfied with statements that data matches predictions and so it isn't necessary to actually fly to limits or demonstrate operational tasks. Politicians don't feel comfortable voting large sums of money for production of an aircraft which has not shown its capabilities in a manner they can understand. For example, the C-17 had to fly an operationally representative airlift mission in the middle of development testing to satisfy congressional concerns, despite the fact that test data showed that the aircraft could perform that particular mission without difficulty. Likewise, commanders don't feel comfortable endorsing or accepting a weapon system which has not been thoroughly "wrung-out." And, operationally-representative tasks may be as revealing of system performance as V&V data collection.

4.1 An M&S Role in Flight Testing

The results of the prior design and development efforts form the basis for flight test planning. For the flight tester, M&S results allow a better understanding of the vehicle before flight. The predicted in-flight characteristics are a critical element in the selection of test methodology and in the hazard analysis preceding flight testing. The test can then be efficiently designed to provide the data to validate the models, compare with simulation results, explore predicted problem areas and demonstrate the overall effectiveness of the air vehicle. This usually result is a reduced test matrix, with time and cost savings. When flight data do not compare well with predictions, the models are adjusted to provide new, and hopefully more accurate, predictions before continuing the testing. In short, the predict-test-compare discipline is already in place.

The M&S processes are an essential element of safe and efficient flight testing, not a substitute. However, predict-test-compare is a methodical approach which may not necessarily save time. A full regimen of subsystem and integration simulations and ground tests for every change to the system after flight testing begins can be extremely costly and time consuming. Sound engineering judgment can determine the minimum requirements. Also, when a highly instrumented test aircraft is available, it may be quicker and less costly to investigate problem areas in flight rather than through analytical means. When unexpected problems are identified, such as system failures or design deficiencies uncovered, the predict-test-compare cycle can be broken. Concerns over schedule and budget disruption, plus fear of the problems generating hasty and adverse judgments by policy-makers, tend to drive testing to a *fly-fix-fly* mode. Some corrective measures for aircraft faults can be quickly derived without the same level of M&S effort which preceded flight testing. A general sense of optimism may underlie the readiness to accept the *fly-fix-fly* approach in the belief that only a minor system change is needed to correct the problem. With sufficient program pressure and a failure of the quick fixes to resolve the problem, the fly-fix-fly mode can rapidly become business as usual.

4.2 Necessary Features of Flight Testing

Some characteristics and functions of an aircraft require a methodical flight test progression, even to check predictions or to collect sufficient data to correct design deficiencies. The very nature of current flight test techniques often dictates the necessary extent of flight testing. Some tests require a considerable quantity of data (e.g., flight performance), test repetition (e.g., bombing accuracy), repeated regression tests (e.g., following flight control revisions), or build-up and safety precautions (e.g., high angle-of-attack clearance). Curtailing large portions of a flight test program must be based on confidence in the maturity of supporting analytical methods. For example,

sufficient uncertainties in aircraft performance predictions (range, endurance, etc.) remain (note the F-111, F/A-18A, T-45A, C-17A in the tables) and the traditional testing approach cannot be circumvented without unacceptable operational implications. Flutter envelope expansion and high angle-of-attack characteristics cannot be safely spot-checked without a reasonable safety build-up, whatever the confidence in the models. These considerations, coupled with the usual unexpected flight test results, may greatly restrict the amount of flight testing which can be eliminated. The potential implications of not performing the necessary testing in the proper manner is potentially unsafe testing and poor quality results.

The experience base of personnel and testing assets must be available to undertake a traditional flight test approach when predictions fail to match flight test results. Even concentrating the increased M&S reliance on avionics and system integration may not yield a large reduction in cost and development time because of the number of deficiencies continuing to be found in flight test which must be addressed by system changes (witness the B-1B of 1984, Table Ia, and C-130J of 1996, Table IIb). On the other hand, changes in flight test processes, such as testing vital system characteristics or those of high technological risk as early as possible, could help to support early production decisions with less program risk and without sacrificing the beneficial aspects of a thorough flight test program.

4.3 And Each Have Their Limitations

There are five factors which can lead to M&S yielding an inadequate design. These are:

1. Use of inadequate M&S tools (e.g. lacking sufficient accuracy or fidelity)
2. Improper use of the M&S tools (e.g. incorrect assumptions, wrong model for application, etc.)
3. M&S results lacking sufficient validity or veracity leading to non-optimal program decisions
4. Inadequate or insufficient use of the M&S tools (e.g., excessive resource constraints)
5. M&S activities insufficiently integrated in themselves or with other development activities

The Tables at the end of this paper illustrating inadequate design characteristics are the result of only a superficial literature search, and are by no means exhaustive. It is important to remember that in each program for which deficiencies are listed only a relatively few aspects of the aircraft were found wanting and M&S suitably predicted system characteristics, in general. Even programs considered extremely successful and which made extensive use of M&S during development (note the 777 data in Table V) experienced surprises similar to programs considered more troubled. Even upgraded or revised designs tend to be large steps in technology and complexity which present similar challenges, with the same sort of deficiencies found in test and service (see the E-6A and T-45A in Table IIa and the F-15E in Table VIb). Of course, there are usually several views on each deficiency uncovered during flight testing or later service, with some people insisting that the problems were known previously or that management decisions, not engineering, were at fault. For example, different individuals have blamed the low durability of the C-5A wing (Table Ia) on such factors as poor management decisions because of program pressures, a lack of practical experience or empirical data, immaturity of the analytical tools at the time, the use of inappropriate analytical tools, or improper use of the right tools. However the "unexpected" characteristics come to be built into aircraft and uncovered in flight, they are still causes for program delays, expanded testing, system revisions, additional program cost, and usually aircraft deployed to fleet operators with numerous waivers, deviations, and restrictions.

There are numerous cases where even detailed flight testing failed to uncover dangerous aircraft characteristics (see Table VI). Typical examples are demonstrated by the instances of flight control deficiencies (departures from controlled flight) shown in the table for several fighter aircraft. Despite lengthy and sometimes hazardous flight control system development and evaluation flight test programs, operational aircraft later experienced unexpected and dangerous events and fleet losses. Detailed simulation and flight testing were required to isolate these problems and prove-out the corrective actions.

There are cases where flight characteristics of an aircraft have never been successfully modeled. The F-16 suffers from a heavy store oscillation phenomenon (Table VIb) which has defied reproduction in wind tunnels or computer modeling.[3] Only flight testing has proven effective in defining the flight regimes where the oscillation is unacceptable. An example where the premature reliance on M&S produced catastrophic results was the first flight of the Pegasus XL air-launched commercial rocket. Because the XL was a growth version of an earlier Pegasus vehicle, the decision was made to dispense with wind tunnel and flight trials and to rely entirely on mathematical modeling for the aerodynamic flight phase. The modeling was used to provide overall confidence in the design of the vehicle and to render the aerodynamic coefficients for the flight control computer. However, the modeling yielded some coefficients which were incorrect - as later wind tunnel testing revealed - and this led to the loss of the first flight vehicle during launch.[4]

The accuracy of the M&S resources are limited by the state-of-the art. Premature reliance on immature resources will likely yield disappointing results. Both the C-17A[5] airlifter and the B-2A[6] bomber under-predicted the temperature and acoustic environment behind their engines, requiring significant design changes after the aircraft were in flight test and production (Table III and

IV). At least in the case of the C-17, measurements had been taken behind engines on test stands, yet the final design was still inadequate. Also, the ability to predict the fatigue life of aircraft metallic structures has repeatedly been shown to fall short of the required accuracy (see the C-5A with first flight in 1968, Table Ia, and the F-16 with first flight 1976, Table VIb). Structural cracks continue to appear, requiring sometimes extensive and expensive corrective actions or operating restrictions. These failings may point to a lack of suitable mathematical models, empirical data, service experience, or design guidelines, and a general inability of the designers to support their choice of design margins against weight reduction efforts later in development.

4.4 No Trend Towards Less Flight Testing

The extent of a flight test program is dictated by the maturity of the aircraft systems, the nature of the mission, the engineering requirements of the test methods, the confidence in the predictive tools, and the design deficiencies uncovered in the course of testing. The programs recorded in Table VII are all different in these aspects. Yet, the data generally shows that there has been no substantial decrease in the number of test aircraft, flight hours, or duration of the testing over the last 30 years, despite a tremendous increase in the use of M&S during development and advancements in the flight test engineering science. All this can be attributed to the greater fidelity demanded of the system, the advances in the state-of-the-art which continues to require detailed testing because of design uncertainties, and the basic limitations of flight testing already discussed. For example, the flight test of the 777 airliner required more than twice the number of flight hours (more than 3,800 flight hrs) than the earlier generation 757 and 767 (1,600 hrs each) because of the complexity of the aircraft and nature of the development program (ETOPS requirements, for example).[7]

The results shown in Table VII are not for want of trying to reduce flight test requirements. Test planners naturally work within schedule and budget constraints, and they have become more attentive to these in recent years as both have been tightened. Revised test methods and equipment have supported these efforts. There may be exercises to cut testing because of a tightening of the constraints, but testers and managers must be empowered to limit such actions when the quality and safety of the testing is jeopardized. It is clear, however, that the flight rate on test aircraft has substantially increased in the last decade. If the system design and the testing process cannot justify a dramatic reduction in flight testing, mandating such a reduction would be a grave mistake.

Many observers have pointed to the commercial airline industry as a model of how military air vehicles can be developed with much fewer resources. Airliners generally undergo only about one year of flight test, much reduced in scope and risk compared with military test projects, before certification and delivery of the first production article to a customer. However, there are some very important differences between the nature of military and commercial aircraft and their certification processes which make such a comparison inappropriate. The commercial aircraft industry generally relies on technology already developed and proven by the military. Airliners have undergone little change in fundamental design philosophy since the 1960s (apart from the introduction of digital flight controls - another military spin-off). Thus, requirements for certification are considerably less than for a military aircraft because of the very limited mission of an airliner and general confidence in the design tools. Airliners also have instances of design deficiencies only uncovered through flight testing (see Table IIb and V), and other problems which got by the testers and have led to some fatal accidents (see Table VIa). In contrast, military aircraft frequently include completely new and unproven technology introducing more uncertainties into designs which, themselves, may be very different from the preceding generation. Because of these factors, plus the vastly more varied and dynamic nature of the military mission, the certification process for warplanes naturally requires more flight testing than commercial aircraft.

Observers have also pointed to the quick results achieved in the very brief YF-22 (91 days, 74 flights, 2 aircraft, 91.6 flight hours) and YF-23 (104 days, 50 flights, 2 aircraft, 65 flight hours) demonstration/ validation flight test program as examples to emulate. However, the dem/val example is not an appropriate comparison with full scale development flight testing. The development program for the F-22A is currently planned to require 60 months and 5,500 flight hours with 13 aircraft. Likewise, the Advanced Concept Technology Demonstration (ACTD) approach does not meet the requirements of development test and evaluation (DT&E) and operational test and evaluation (OT&E), and was never meant to.

There are no simple routes to less development flight testing, but only a steady effort to shift the balance between it and M&S through progressive engineering and management changes.

4.5 Requiring a New Mind-set

A flight test setting out initially to collect data for M&S validation would not necessarily proceed in a manner comparable to past programs. Traditional methods of measuring progress, such as flight rate and percentage complete, will likely no longer be valid. A "'linear' progression in terms of altitude and Mach envelop cleared, greater gross weight and attitude progression, higher airloads, drag polars flown, etc., may have no meaning. Many tests will not be operationally representative and may make the system look 'bad,' yet still yield vital data. A set schedule for flying test points within a test plan may not be possible because of the need to analyze data,

compare with predictions, adjusting and rerun the model, and use the results to guide the selection of the next flight test points. Unexpected results could require a change in the planned testing to allow the collection of required data to investigate the anomaly - including the employment of traditional 'linear' test methods. Adhering to a routine flight schedule would probably result in superfluous or irrelevant data depending upon the analysis of the initial results, and take engineers away from more productive analysis activities. A program conducted in this new manner may require the same or less resources and time as a program conducted along traditional lines, but a new mind-set must be instilled to allow it to run its course unimpeded. A more flexible scheduling of test flights and objectives are required to allow sufficient time for analysis without undue time pressures and to ensure that only useful tests are conducted. Demands from program officials or leadership outside the program for progress metrics need to be reduced and more suitable measures developed.

5.0 IMPROVING THE IT&E PROCESS

Some of the activities now underway or needing to be addressed in shifting the balance between M&S and flight testing include:

1. Seek new flight test methods and tools to reduce time and cost, plus provide higher value data
2. Better integration of M&S and flight testing activities earlier in the development process
3. Proactively seek ways for M&S to further help reduce flight testing
4. Technology investment into better M&S tools and processes

It is the last initiative which this paper's proposal particularly facilitates.

The endemic uncertainties in M&S make it difficult to isolate the source of failures to match actual flight test results. Unexpected flight test results are frequently dealt with by simply making small changes to analysis coefficients, altering system gains, or other such measures. Unless a detailed review reveals the root cause of the failure to predict the flight test result (why was the incorrect coefficient or gain chosen in the first place?), the same error will probably be made on the next program - where it may have more serious consequences. The improved understanding of the models and analyses supporting an existing system which result from such a practice would also be invaluable during sustainment throughout a system's life where these tools will be used during problem resolution, modifications and upgrades. Benefits will be seen in reduced life cycle costs. However, there appears to be little discipline at present to perform such reviews.

This author has seldom found that rigorous error analysis was performed on the engineering predictions supporting a flight test. Such an analysis would highlight the elements supporting the predictions which possess the greatest error. This will help in clarifying reasonable expectations from current methods and processes, and in setting achievable goals for improvement in areas revealed to have the greatest overall affect on accurate predictions. An assessment of the maturity and limitations of both M&S and flight testing must underlie any effort at improvements to reduce the latter.

Tracking the sources of the M&S errors is frequently difficult during or after flight testing because much of the laboratory testing and analyses are years in the past and many of the personnel involved at that time have scattered. However, an effort *must* be made to follow these paths back as soon after discovery of deficiencies as possible, to learn from these mistakes, and to improve the process. Managing the shift in the balance between M&S and flight testing will require this sort of closer dialog and problem resolution between testers and analysts within the context of integrated test and evaluation (IT&E).

If the initiative to displace large portions of flight testing with M&S is to be successful, then these tools must be improved using the results of recent and on-going flight test programs. It is important that this investigation process be undertaken <u>during</u> a test program while memories are fresh and before personnel have moved on. The improvements would best be achieved by directly addressing demonstrated failures to predict flight results. An investigation of such problems may involve little more than reviewing data and rerunning computer programs. Determining the areas of greatest uncertainty or potential error gives insight into the key areas on which to focus research. Laboratory or ground tests may be required to quantify tolerances or provide data for revised modeling. Likewise, some flight testing may need to provide additional data, to try alternative methods, and to verify revised predictions. More deeply-rooted deficiencies may require some experimental research. This may involve basic laboratory research or experimental flight research to collect basic data for validating new models. Publishing the results of the investigation and research is important to help make the aerospace industry aware of whatever changes are recommended. The government laboratories become critical to direct and finance the research and to demonstrate solutions. Test centers must have the means to investigate new and more efficient ways of testing for V&V data without relying on major programs to finance this activity. This proposal for improving the IT&E process to increase the reliability of M&S will depend upon the communication, cooperation, and commitment of the various program offices, test organizations, contractor teams, and government laboratories.

5.1 Example Problem Review & Assessment

This section represents some basic literature research and personal interviews into one area of aircraft development engineering where deficiencies have become evident.

This was done to serve as a simple example of an initial problem investigation process. The resulting considerations would be a first-level outcome of such an investigation. Follow-up actions would include determining the best course of action for researching solutions to the problem along the lines suggested, possibly using study contracts or test projects.

5.1.1 Pilot-Structural Coupling in Large Fly-by-Wire Aircraft

An example of an M&S deficiency appears to lie in the failures to predict and avoid instances of pilot coupling with aircraft structural dynamics through the digital flight controls. Even if not hazardous, the resulting oscillatory instability in aircraft response is an intolerable handling qualities deficiency. The problem has occurred in the past on many types of aircraft, including fighters. However, the instabilities have recently been experienced on a number of large developmental aircraft, including the V-22 (Table IIb), the C-17 (Table IV), and the 777 (Table V). These are all very different aircraft developed in approximately the same time frame and representing some of the first instances of electronic flight controls being mated to large airframes with strong structural elastic modes of response within the pilot bandwidth. These three examples - nearly every large fly-by-wire aircraft developed in the US - illustrate this.

It is important to avoid experiencing these instabilities in flight test because of the time and expense required in remedying them. Corrective actions normally consist of all or some of the following: an analysis to determine the required changes to the flight control laws or aircraft mechanical control mechanisms; recommendation and review of the proposed changes with approval to proceed; computational trials with the corrections to ensure that they perform properly and don't produce new problems; pilot-in-the-loop simulations to ensure suitable handling qualities; hardware-in-the-loop ground tests to verify suitable gain and phase margins without limit cycle oscillation instabilities; preparation and testing of operational flight program (OFP) software to be loaded into the test aircraft; regression flight testing to ensure that the fix works properly without producing detrimental handling qualities elsewhere in the flight envelop or other difficulties; preparation and approval of detailed documentation for the change; and release for installation of the OFP to the fleet. This process has been known to take up to six months or longer, with associated expense.

5.1 2 The 777 Airliner

A 777 pitch oscillation resulted from rapid yoke inputs in pitch, simulating a pulsing technique used by some pilots. A fuselage bending mode could be excited by these inputs, with a tendency for the pilot to couple with and sustain the dynamics. As pilot gains increased in proximity to the ground, the tendency to couple also increased.[8] Revisions to the system control laws corrected the problem. The development of the 777 flight control system (FCS) included modifying a 757 aircraft to a fly-by-wire configuration with the 777 developmental control laws and computers. Although the test aircraft had different structural modes than the eventual 777, the test still provided an outstanding opportunity to evaluate the potential for pilot-in-the-loop instabilities with the developmental control system. The 777 program does not appear to have conducted any Motion Based Simulator (MBS) work, with dynamics representing the notional 777, during development. The reasoning behind this decision was probably affected by the use of the 757 demonstrator, the fairly low FCS gains used for the airliner mission, and the perceived ease of making FCS changes rapidly during the course of the coming flight test. The program results appear to have justified these decisions.

5.1.3 The C-17A Airlifter

In the case of the C-17A airlifter[9], the development process included analytical modeling and analysis for pilot-in-the-loop instabilities. This resulted in the design of digital filters and choice of gains within the flight controls to ensure sufficient phase and gain margin and the prevention of instabilities. This work included a mathematical model of the aircraft elastic response, provided by the structures analysts, and a model of the pilot dynamics. Initial pilot-in-the-loop simulation work in support of the analytical methods (Phase III, 1987) was performed in a motion-based simulator. This showed evidence of a roll ratcheting response, but the fidelity of the simulator was so poor that nothing revealed by the testing was felt to be usable. Testing resumed (Phase IV, 1989) in the Ames Vertical Motion Simulator (VMS) where the ratcheting was seen again. The response seemed to be dependent on whether the pilot had an elbow on the arm rest or not, suggesting a limb-bobweight influence and pilot-structural coupling. The airframe contractor felt that the response was a problem with the simulator while the VMS operators felt that it was a flight control characteristic. The mode of the response was close to a natural mode of the simulator, but not identical. The contractor worked to change the flight control system to eliminate the problem, and it was not seen in later MBS tests. The later testing (Phase V with limited MBS work and Phase IX with full MBS) used a position-sensing stick rather than the earlier force stick. The potential for pilot-in-the-loop instabilities was considered reasonably great by some members of the flight test team because of the fairly high C-17 FCS gains required for the aircraft's tactical mission. In addition to several pilot-induced oscillation cases, a roll ratcheting response resulting from a coupling of the pilot's unintentional lateral stick response with asymmetrical bending of the wing appeared during flight testing. The dynamics were considered unacceptable from a handling qualities perspective and also resulted in structural overload. A series of revisions

to the FCS were required as some change to solve the problem tended to degrade desirable handling qualities and prompt additional revisions. Two other instances of pilot-structural coupling were attributed to abnormalities in the mechanical control system.

While a MBS should be able to simulate structural responses within the bandwidth of the pilot, the simulators used by the C-17 did not have the computational and computer through-put capacity to run a simultaneous, high fidelity, real-time, pilot-in-the-loop flight simulation combining both FCS and structural models. Therefore, only a very simplistic structural model was used. Most or all of the models were linear to reduce computational time and volume. Further, although the structures analysts seemed to be able to predict the structural modes well, later flight test results demonstrated that they fell short on predicting the airloads. These loads provide the forcing function for oscillatory behavior, determining the power of the modes and the resulting moments at the pilot station. Thus, the structural model used during the FCS development was likely deficient in this regard. These factors may have contributed to the failure to observe the ratcheting in later MBS work. Also, the C-17 engineering team was not well integrated. The structures team would pass models and phase/gain relationships to the FCS team, but the teams did not work together during Fixed Base Simulator (FBS) or MBS testing to best understand what was being learned or the limitations of the simulations. Engineers associated with the program disagree about whether the roll ratcheting could have been predicted and corrected prior to flight.

5.1.4 The V-22 Tilt-Rotor Tactical Transport

The V-22A Osprey has many low-order structural modes within the pilot's bandwidth as a consequence of its unique design. Numerous instances of pilot-structural coupling were discovered during flight testing.[10] These included: a rigid body roll oscillation through excitation of a roll mode; a coupling with an asymmetric wing fore-aft mode through longitudinal stick motion; coupling in airplane mode with a symmetric wing fore-aft mode through longitudinal stick and the thrust control lever; coupling with a wing bending mode creating a bouncing motion during approach to hover; and coupling with a wing fore-aft mode during speed changes while carrying a sling load. The characteristics were corrected through a combination of FCS software revisions and mechanical system changes.

Engineers associated with the V-22 reported that the development team appreciated the potential for pilot-structural coupling in their aircraft. A structural model was included in the transfer functions for the aircraft used in designing the flight control system. However, a pilot model was not included until after first flight. Both the structural and pilot models have been progressively improved using ground test and flight test data. Limb bobweight and arm stiffness was accounted for in the pilot model at later dates. Large excitations or maneuvers to excite the structure were not analyzed. Also, while MBS work was performed, structural models were not included in these evaluations. These engineers, amongst others who were interviewed, stated that the limitations in modeling and simulation make prediction of all possible instabilities prior to flight an unrealistic expectation.

5.1.5 Considerations

The instances of pilot-structural coupling presented here appear to be the result of mating a large, highly elastic airframe with an electronic flight control system. Any number of design processes may have been responsible for allowing these problems to occur. For similar -and possibly any - designs, the research yields the following considerations.

1. There must be sufficient appreciation of the potential for pilot-structural coupling and a willingness to use resources to avoid possible deficiencies in this area.
2. Aircraft flight control models should incorporate high fidelity pilot and structural models.
3. The development team should have a commitment to performing motion-based simulation (MBS) testing.
4. MBS must be able to faithfully simulate structural responses within the bandwidth of the pilot.
5. The MBS tests should be run with a structural model of sufficient fidelity, probably nonlinear, for the best chance of uncovering possible coupling instabilities.
6. The industry must strive to add more computer power to MBS systems to allow simultaneous and high fidelity FCS and structural modeling with nonlinear mathematical tools.
7. Every MBS test should include an analysis of the simulation limitations (bandwidth, attenuation, resonances, roll-off filters, etc.) and their possible effects on the test results.
8. There must be a willingness to simulate sharp inputs and aggressive maneuvering in the analytical and MBS modeling to excite structural responses and produce high gain states for adequate evaluation of potential coupling instabilities.
9. The structures and FCS teams must be well integrated for the analytical, MBS, and flight testing to allow a full understanding of the implications of what is observed and of the conclusions drawn.
10. If any of the actions addressed above are short-cut because of schedule and budget constraints, the potential implications in terms of discoveries during flight testing and revisions to the FCS software must be understood, accepted, and appropriate measures taken.
11. Flight test teams must appreciate the possibility of pilot-structural coupling and design the testing to evaluate this potential.
12. There must be a willingness to perform flight tests with sharp control inputs, aggressive maneuvering, and high gain states to adequately evaluate the potential for pilot-structural coupling.

13. Researchers should examine instances of pilot-structural coupling in recent programs and attempt to determine the source deficiencies in the developmental tools and methods employed.

14. Researchers should evaluate the possible need to improve the fidelity of the pilot models used in flight control models.

15. Researchers should evaluate the need to develop easier and higher fidelity means of inserting the structural dynamics into the flight control model transfer functions to promote this sort of analysis.

16. Researchers should evaluate the need to develop a criteria - such as magnitude of structural damping, magnitude and sense of accelerations at the pilot station from structural dynamics, etc. - which would indicate potential pilot-structural coupling and prompt appropriate analysis and testing during development.

17. Researchers should attempt to follow-up on at least one such case of failure to predict an instability in order to verify their conclusions or try different approaches. The latter may include revising and rerunning analyses, repeating MBS tests, collecting additional flight test data. etc.

18. Researchers should determine typical errors in current analytical models, computer codes, simulations, etc. (error in prediction of structural modes, airloads, stability derivatives, etc.). They should attempt to define error expectations for these elements. They may then use these results to guide recommendations for improvement projects.

19. Researchers should assess the need for revisions to design handbook guidance or other documentation with the intent of reducing future potential for unpredicted pilot-structural coupling.

6.0 CONCLUSION

The best balance of M&S and flight testing in aircraft development is determined by the perceived reliability of engineering predictions, the requirements of a logically planned and safe flight test program, and the need to address deficiencies uncovered during the testing. The balance has been shifting toward M&S as these tools have expanded and improved, but a dramatic reduction in flight testing cannot be imposed without introducing unacceptable program risk. The risks lie in the increased likelihood of producing and fielding weapon systems which simply do not perform adequately and which presents hazards to the operators. To reduce such risks, M&S design tools must be improved and validated by learning from each failure to match flight results. The decision to place more reliance on M&S, as a design tool, must be made because it has a high potential for producing a better product more quickly and at reduced cost, not because of politically-expedient motivations or poor program management choices.

Modern combat aircraft are so complex that it has not been possible to replicate all conceivable influences and interactions through ground testing or computational analysis. The likelihood that unexpected results will occur in flight testing is great because of this and because designs continue to push the state-of-the-art. Flight testing and M&S are both essential elements of a development process which has been repeatedly shown to take as long as is necessary for a successful new system. Major design deficiencies and large program overruns have demonstrated the fallacy in trying to accelerate the process artificially. If a program is moving so fast that time is not available for a thorough flight test using proven methodologies, then it is probably moving too fast and is headed for trouble. Despite such efforts, the need for detailed flight testing appears to be as essential now as in the past. The balance of modeling & simulation with flight testing must be managed to allow the right decisions to be made for the right reasons.

7.0 REFERENCES

1. Benek, J.A., Langham, T.F. and Baker, W.B., Jr., "Historical Perspective on the Integration of Testing and Evaluation Methodologies at the Arnold Engineering Development Center", AIAA-94-2470, June 1994.
2. Cranston, S.E., "Reinventing T&E -- At the Base Level, The AFDTC Perspective," *in* "Proceedings of the ITEA International Symposium", 2-5 October 1995, pp 103.
3. Norton, W.J., "Limit Cycle Oscillation and Flight Flutter Testing," *in* "Proceedings of the 21st Annual Symposium of the Society of Flight Test Engineers", August 1990, pp 3.4-1.
4. Smith, B.A., "Model Error Led to Pegasus Failure", Aviation Week and Space Technology, 1 August 1994, pp 28.
5. Smith, B.A., "Flight Testing Pace for C-17 Under Review", Aviation Week & Space Technology, 26 April 1993, pp 20.
6. Morrocco, J.D., "Air Force Prepares to Operate B-2 Bomber", Aviation Week & Space Technology, 13/20 December 1993, pp 29.
7. Proctor, P., "Early Modeling Helps Speed 777 Flight Testing", Aviation Week & Space Technology, 12 June 1995, pp 124.
8. Cashman, J.E., "Boeing 777 - Progress to the Plan", *in* "Proceedings of the 39th Annual Symposium of the Society of Experimental Test Pilots", September 1995, pp 4-16.
9. Kendal, E., "C-17 Flying Qualities & Aircraft-Pilot Coupling, (APC), Experience During the Development Process", McDonnell Douglas Transport Aircraft, November 1995.
10. Lunn, K., Dunford, P.J. and Sullivan, P., "V-22 Tiltrotor Development & Flight Characteristics", *in* "Proceedings of the 23rd Annual Symposium of the Society of Flight Test Engineers", August 1992, pp 1-86.

Table Ia
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

Programs Before 1985

REQUIREMENTS	NOTES
F-111 bomber (1964)	challenging performance requirements for very broad mission, innovative swing wing design
unacceptable performance (range, acceleration, etc.) due to excessive drag, inlet inefficiencies	multiple redesigns of intake, engine revisions, more powerful engine in later models
engine susceptible to stalls due to inlet incompatibilities, turbulent flow	multiple redesigns of intake
multiple avionics system deficiencies	multiple system changes
C-5A Galaxy strategic airlifter (1968)	many structural design challenges
wing had only ¼ of required durability, extensive cracking experienced in fleet	fleet groundings, new wings designed, manufactured, and retrofitted to entire fleet after four years
engine mounts understrength, design deficiencies with ailerons	fleet limitations from full thrust & maximum airspeed, redesign and modifications
landing gear mechanical problems	redesign and modification, 4 years to make acceptable, still high maintenance item
unexpectedly high structural flexure with hydraulic leaks, caused fire which destroyed a test aircraft	redesign and replace hydraulic line fittings
development problems with automatic flight control system (AFCS)	2 year late deployment to fleet
unacceptable performance from multi-mode radar and doppler-inertial navigation system, low reliability	unknown
B-1A bomber (1974)	new design with many challenging features, development halted with program cancellation
severe weapons bay environment due to adverse airflow and acoustics, vibration of bay doors	added actuated spoilers ahead of bays
fatigue cracks in horizontal stabilizer trunnion and skin due to unstable transonic shocks	redesigned
F/A-18A Hornet fighter bomber (1978)	redesign of YF-17 demonstrator but essentially new design, many design innovations
unacceptable performance (range, acceleration, etc.), excessive drag	redesigned leading edge extension, wing leading edge radius and snag, ECS exhaust, changed slat schedule
unacceptably high nose wheel liftoff speed	redesigned stabilators, revised flight control software to toe in rudders and reduced leading edge flap angle
unrecoverable flat spin mode, aircraft crashed	revised flight control software to incorporate override bypassing some flight control logic
low roll rate plus g excursions due to deformation of wing, loads stalling LE flap actuators, stick torquing	used other surfaces for roll, redesigned wing for greater stiffness, added area to ailerons, removed LE flap snag
time delay, dutch roll, control sensitivity in two axes, and HUD display made tracking unacceptable	unknown
heavy store oscillation with annoying motion at pilot station	revised flight control software to actively damp oscillation using ailerons
leading edge extension vortices impinging on vertical tail causing vibration and fatigue cracks	strake added to leading edge extension, revised vertical stabilizer manufacturing process
fatigue cracks in fuselage bulkhead	redesign and modification
unacceptable radar reliability, radar slow to lock under g, resolution deficiencies, high BIT error rate	system changes

Table Ib
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

Programs Before 1985 (continued)

REQUIREMENTS	NOTES
F-117A bomber (1981)	radical features tested with scaled proof-of-concept demonstrator, F-117 used much existing hardware
directional axis stability and control power less than predicted, unacceptable	tail surfaces redesigned, area increased by 50 percent
flutter caused most of one tail to separate, safe recovery to base, flutter testing already completed	conservatism in analysis hid potential, redesigned tail and stiffened tail control friction, additional testing
10 Hz outer wing oscillation during rolling pull-outs, zero outboard elevon hinge moment	stiffened outboard elevon actuator control axis and reduced freeplay
change to fuel transfer sequence (unknown reason) gave a decrease in wing inertial load relief	strengthening of the wing aft attach structure
aft fuselage airloads greater than predicted, down bending produced by unusual engine exhaust system	additional flight testing, no change reported
other problem with unusual engine exhaust design: hot spots, tailpipe distortion	unknown design changes, additional testing
shearing of engine power takeoff (PTO) shafts	unknown
air data probe problems when heated: cracked, calibrations drifted, pitch axis pilot-induced oscillation	changes to probe design, increase in hole size, improved manufacturing quality control
difficulties with retractable antennas at high airspeeds, some structural failures	modifications, additional flight testing
navigation steering mode did not function properly	system revisions
multiple problems with Infrared Acquisition and Detection System	major effort to correct, additional testing
Weapon System Computational Subsystem could not start up correctly and suffered inflight failures	revised system
system initially would not allow GBU-10 laser guided bomb to guide after release	software fault corrected
unacceptable intercom background noise	increasing the number of grounds in the system and improving line shielding
the number of system integration problems and short test schedule threatened initial operational capability	crash effort to test minimal capability for deployment, many years to complete all tests originally planned
B-1B Lancer bomber (1984)	significant redesign of B-1A with very rapid development, testing, and deployment
several instances of undesirable handling qualities (fleet limits in maneuverability, weapon and fuel)	major and repeated revisions to flight control system, additional testing, fleet restrictions, years to resolve
false fly-ups and unexpected pitch-overs during hazardous terrain following radar flight testing	significant additions to flight control system over several years, fleet restrictions, additional testing
defensive avionics suite did not operate properly and did not meet operational requirements	considerable redesign, additional flight testing, great expense, fleet without full system for about 10 years
undesirable store separation characteristics	unknown

Table IIa
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

Programs Since 1984

REQUIREMENTS	NOTES
T-46A trainer (1985)	low technology risk design
trim rate slow and low effectiveness, aileron forces high, stick forces high on takeoff	enlarged trim tabs, aileron control system revised and moved hinge line aft, changed stick-elevator gearing
excessive drag with speedbrake deployment, top speedbrake caused nose down pitch, excessive buffet	reduced deployment angles
wing/aileron flutter experienced after aileron balance changed	unknown, flutter found in analysis after event by increasing analysis conservatism
E-6A Tacamo airborne communication platform (1988)	conversion of 707 airliner with changes to vertical tail design for easier and less expensive manufacture
vertical tail flutter and partial loss of surface on two occasions (similar to problem in KC-135A testing)	delivery delay, 2 yr fleet airspeed limitation, limited abruptness of rudder input & structural changes
minor wing tip flutter	unknown
trailing wire antenna struck tail during 50 degree bank turn	unknown
T-45A Goshawk trainer (1988)	derivative trainer design, converted for carrier operations
performance less than predicted, inadequate for waveoff and bolter, poor glide slope control	modification to add additional fuel volume, changed to upgraded engine, increased idle RPM for approach
engine surges during throttle snaps in wave-off or bolter carrier operations, lag in throttle response	change to fuel control system
engine surge with steam ingestion from catapult system	revised engine control system to increase surge margin by increasing bleed offtake during catapult operations
longitudinal instability due to stick free control system oscillations at high Mach numbers	rebalanced control system, control rod to elevator gearing changed, added viscous damper to system
inadequate lateral-directional stability, excessive adverse yaw and dutch roll, poor roll response	added ventral fin plus added 6 inch cap to vertical tail/rudder, multiple revisions to control system
inadequate stall warning and excessive roll-off in power approach, approach speed too high	added retractable wing slats, squared wing tips, added rudder shaker and area to stabilators, additional testing
pilot-induced directional oscillations during landing roll-out	added dual-gain nose wheel steering feature, low gain activated on touchdown
unacceptable spin characteristics and rudder blow-out, recommendation against use for out-of-control training	additional testing, possible revision to Naval aviator flight training program, debatable future impact
anti-spin parachute structural failure during attempt to recover from spin (non-standard equipment)	recovery successful, modification to anti-spin chute system and chute packing
rudder vibration near the edge of the airspeed envelope due to unstable shock waves	added full span shock stabilization strips to the rudder
low speedbrake effectiveness	modified speedbrakes system to modulated control, added deployment indicator to cockpit
undesirable trim change with speedbrake deployment due to airflow interaction with horizontal tail	added speedbrake-to-stabilator interconnect
higher than expected wing attach link loads during carrier landings	modified with additional lateral wing/fuselage attach link
tailhook struck tailcone on rebound from cable release	additional upstops/bumpers installed

Table IIb
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

Programs Since 1984 (continued)

REQUIREMENTS	NOTES
V-22A Osprey tactical transport (1989)	new and challenging design, many radical features
hover lift less than predicted	employed download alleviation techniques and uprated transmission
many instances of pilot-structural coupling	revised flight control system software, mass balanced stick lateral axis
pilot-induced oscillation susceptibility during lateral maneuvering, in-ground-effect hover, and on ground	mass balanced cyclic, revised flight control system software and incorporated lateral swashplate gearing
high pitch control sensitivity in airplane mode	reduced elevator gearing and revised flight control system software
pitch coupling with sideslip at low speed due to rotor wake/empennage interaction	increased longitudinal cyclic range 3 deg, automated nacelle control at high longitudinal cyclic settings
negative dihedral stability and yaw/roll coupling in helicopter/conversion mode	reduced pedal to differential cyclic gearing and augmented yaw control with differential collective
high workload in hover, low speed and conversion, control system deadband a contributor	revised flight control system software and hardware, introduction of autoflap function during conversion
sluggish vertical response in hover	revised flight control system software and implemented Torque Command Limiting System
force deadband degraded precise control of trim	control system improvements
lacks clear indication of stall onset	unknown
excited asymmetric drive system response following lateral control input, excessive torque overshoots	revised flight control system software
nacelle/wing vortices impinging on tail causing uncomfortable vibrations	installed wing fences, pendulum absorbers on rotor hub, and vertical tail mass balance weight
excessive empennage unsteady airloads during maneuvering	additional wind tunnel testing, possible correction is addition of forebody strakes, additional flight testing
some rotor component flight loads above durability limits during conversion	added software to flight control system to relieve loads
engine exhaust impinges in area of avionics cooling inlet, concern about heat on shipboard gear	installed infrared suppresser gas deflectors in engine nacelle exhaust
non-optimal safety design contributed to loss of aircraft in engine nacelle fire and failure of drive shaft	conclusion of crash investigation, numerous minor modifications and system revisions
radio performance less than optimal	modified antennas and changed groundings
flight control computer sensitivity to cold, drive shaft resonance in cold weather, other minor issues	unknown, found during ground climate testing
MD-90 airliner (1993)	derivative design with new engines and revised cockpit
thrust reverser airflow caused heavy tail vibration, concern about structural fatigue	revised reverser cascade design
engine nacelle strakes caused excessive drag, yet important for suitable stall characteristics	reduced size of strake and added engine pylon flaps
C-130J airlifter (1996)	upgrade of existing design with new engines and much revised avionics
considerable avionics integration and interoperability difficulties, over 1000 items to solve	software revisions and problem tracking, first flight delayed 3 months

Table III
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

B-2A Bomber
First Flight 1989

CHARACTERISTIC	CONSEQUENCE
initial failure to meet low observable requirements, although most results within measurement tolerance	minor modifications, additional flight testing
high temperatures on aft engine "deck" caused metal cracking and blistering on composites	use of thermal tiles on composite, increased inspection, ultimately redesigned deck
less stability margin than predicted because of flexibility effects on feedback sensors	unknown
reduced control system stability near edge of operating envelope and certain fuel states	revised flight control software
speed stability too great, high workload, excessive trim change with increase in airspeed and power	revised flight control system
longitudinal stick force gradient too high, hampered pitch control during takeoff and aerial refueling	reduced stick gradient
pitch porpoising during aerial refueling behind KC-135, pilot-induced oscillation tendency	revised flight control software, including throttle-elevon interconnect function
unexpected pitch-ups at elevated angles of attack and sideslip angles during high roll rate maneuvers	defined limits of maneuver envelope, revised flight control software to incorporate limits
drag and pitching moment transient when weapons bay were opened	revised flight control software, additional testing, $3-4 million cost
non-optimal roll-in and roll-out rates	revised flight control software
residual pitch oscillation in narrow operating zone, discovered late in test program	envelope limited, final correction TBD
crosswind compensation feature caused "weathervane" into wind during taxi, takeoff and landing	control surfaces more effective than predicted, revised flight control system software
delay in display of airspeed readings of several seconds, 6-9 knot lag	revised software
software errors caused uncommanded release of a string of bombs	revised software
one CBU store very close to bay doors on release, another struck bay camera	weapon restrictions imposed
poor braking performance, initially weak and "grabbing", caused nose gear "duck walk" dynamics	modified braking control system and changed brake puck size
parking brake requires excessive force (two pilots) to set	revised braking system helped, pedal angle to be changed
terrain following radar could not distinguish rain from obstacles	several revisions to radar software
radome material absorbed moisture, attenuated radar signal	revised radome material, revised software
Manned Alert feature overloaded APU and accessory drive, causing system to drop off line	APU and ECS controller changes, additional testing
flexible ducting in windscreen anti-ice/rain removal system bursting, other system malfunctions	replaced with different ducting, other unspecified system changes
built-in test (BIT) high false alarm rate	revised software

Table IV
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

C-17A Globemaster Airlifter
First Flight 1991

CHARACTERISTIC	CONSEQUENCE
performance (range, endurance, etc.) about 6% less than predicted due to drag and fuel consumption	operationally acceptable but engine revisions to improve efficiency and some gap seal improvements
pilot-structural coupling during abrupt rolls produced ratcheting oscillation and prohibitive wing airloads	multiple revisions to flight control system software, changed aileron/spoiler scheduling, additional testing
pilot-induced oscillation during aerial refueling and some landings	revised flight control system software, additional flight testing, night refueling denied fleet for some time
numerous handling quality and flight control deficiencies	multiple revisions to flight control software and mechanical system, additional flight testing
pressure differences between multiple pitot and static probes caused flight control system anomalies	revised pneumatic plumbing, revised air data computer and flight control system software
many instances of under-predicted or over-predicted airloads, over-loaded structure during flight testing	minor increase in flight manual limitations (slats extended, flaps up), most later determined acceptable
main landing gear shimmy susceptibility, several incidents, many related design and installation issues	retained shimmy dampers with weight, cost and maintenance penalty, revision to gear components
inadequate main landing gear lubrication on some mated surfaces, damaged components	redesigned components and lubrication procedures
accelerated tire wear due to scrubbing during taxi and towing, causes vibration during takeoff and landing	TBD, unsuccessful attempts to correct with changes to tires, vibration required beef-up of avionics rack
high nose gear door airloads prevented nose gear retraction at placard airspeed limit	airspeed restriction until modified with additional nose gear retract actuator installed (door linked to gear)
nose gear extended and retracted with great force, caused hardware cracking	revised hardware and added hydraulic restrictor to over-center lock actuator to reduce force
engines unsuitable for unloaded maneuvers, 2 engines damaged, concern about flame-out potential	none, low operational significance, flight manual verbiage added
engine fire bottle uncommanded discharge at high temperatures, discharge force tore bottle off mount	grounding until system revised and mounts modified, additional testing
fuel system valves freezing and sticking at altitude	manual fuel transfer required until changed model of valves
failure of some thrust reverser components due to excessive vibration	redesign and modification
engine pylon stub mount understrength	slight operational restriction
high flap temperatures and acoustics from engine efflux caused cracking	operating restrictions until flaps redesigned with revised structure and material
core thrust reverser flow heat damaged slat leading edges	operating restriction until slats material changed
aft fuselage airflow increased potential for paratrooper and parachute canopy interference	additional ground and flight testing to determine optimal jump conditions
aft fuselage jacks extended uncommanded, damage, jack doors gapped in flight	revised jack hydraulics, other system changes
crew door not adequately latching, mechanism failures, troop doors could not be opened in flight	revised mechanisms, some redesign and modification
multiple strength and operability issues with cargo door and ramp actuators, locks, cargo system and floor	redesigned components, revised hydraulic components, modified aircraft
high fails alarm rate in built-in test (BIT) system, additional unneeded maintenance actions	revised software, several years to correct fully

Table V
UNANTICIPATED CHARACTERISTICS DISCOVERED IN FLIGHT TEST

777 Airliner
First Flight 1994

CHARACTERISTIC	CONSEQUENCE
leading edge devices less effective than predicted and provided nonideal longitudinal maneuvering stability	redesigned leading edge slats and added vortex generators, 8 configurations tested
yaw and roll-off during stall in landing configuration and poor accelerated stall warning	altered inboard slat gap with hardware change and rescheduled outboard aileron with angle-of-attack
pitch axis pilot-induced oscillation on landing due to auto spoiler, elevator control saturation	revised flight control software, delayed spoiler activation, additional testing
pilot-induced oscillation during flight control system mode transitions and mistrim takeoffs	revised flight control software
pitch axis sensitivity at high airspeed and altitude	revised flight control software
slight buffet with landing flaps at some airspeeds	additional wind tunnel and flight test work, added vortex generators, final solution unknown
minor pilot-structural coupling at 3 Hz with control pulsing technique, generally close to ground	revised flight control software
3 Hz fuselage bending mode excited with heavy braking (on rebound nose gear left ground)	de-tuned by altering timing for application of last brake pairs
inadequate trim compensation in atypical high speed touch-and-go landing with low flaps extension	adjusted trim software
flush static ports affected by nose shock wave	relocated ports
0.01 Mach faster best cruise airspeed than predicted	none
fuel management inaccuracy after maneuvering	software changes
slight lag in engine response to throttle	"tuned" engine control software
instrument sensor in cowling affected engine tachometer reading, engine flameout (relight okay)	unknown
"tone" with Rolls Royce engines disturbed ideal boat tail airflow	unknown correction, 50 additional hours of flight testing
ice impact damage to GE90 engine acoustic panels during icing tests	redesign of hardware and repeat of flight tests
repeated in-flight failure of air-driven hydraulic back-up pump during tests	design changes and additional testing
nose gear aft door vibration	unknown, maximum airspeed for gear retraction reduced temporarily
loss of small service door in flight, ruptured hydraulic line, door unlatched on other occasions	emergency landing, unknown correction
over-center brace not locking in alternate gear drop, side brace incorrect length	unknown
cabin pressurization duct hardware failures on three occasions, depressurizations, persons hospitalized	redesign of clamps, ducts, and internal check valves
nuisance engine vibration annunciation and false thrust reverser "not closed" indication	adjusted sensors
air conditioning temperature control problem	unknown

Table VIa
UNANTICIPATED CHARACTERISTICS DISCOVERED IN SERVICE

CHARACTERISTIC	CONSEQUENCE
777 Airliner	
tail "wag" in turbulence rattles serving carts and causes some nausea (also seen in 747-400, 757, 767)	revised gust response flight control software, some additional flight testing
moist air condensing into "snow" emitted by air conditioning system into cabin under some conditions	ice screens installed over air conditioning outlets
isolated breakups in cargo handling system guide rails and locks	unknown
MD-11 airline	very fast paced flight test program, tremendous pressure to make first delivery date
performance (range, endurance, etc.) less than predicted, one customer canceled order	additional fuel volume added, modifications to reduce drag, improved engine efficiency, 2 yrs to correct
customer complaints of multiple deficiencies, refused to accept further deliveries or place in service	crash effort to affect and check corrections
flap/slat handle design allowed uncommanded slat extension, abrupt pitch incidents, two persons killed	fleet cautions and temporary retainer on handle, ultimately redesign of flap/slat control
ATR42/72 regional airliner	American-certified European aircraft, many operators in US
ice forming aft of wing deicer, reduced stall angle of attack and aileron effectiveness, at least one crash	fleet restrictions, lost sales, additional flight testing, deicer modified with greater chordwise area
C-141B Starlifter airlifter	
wing cracks occurring at less than expected life of design	increased inspection requirements, some aircraft grounded, fleet restrictions, aircraft modified
Commercial airliners and military aircraft	
repeated instances of fatigue cracks in structure within lifetime of airframe, also unexpected corrosion	limitations, grounding, inspections, repairs, additional research into prediction and inspection procedures
B-1B Lancer bomber	
engine fan blade retaining ring failure, 2 engines damaged, fleet grounded	redesigned retaining ring, modification and inspection of engines
fuselage longeron understrength, cracks found in service	some aircraft grounded, inspections and modifications to strengthen member, additional testing
B-2A bomber	
erosion of leading edge protective paint coating by light rain	paint reportedly applied incorrectly, factory processes revised, coating reapplied
UH-60A Blackhawk and CH-47 Chinook helicopters	
turbine engine blade damage and cavity obstruction from sand ingestion, performance loss (Desert Storm)	special intake filters rapidly developed, special maintenance actions mandated requiring more time
UH-60A Blackhawk helicopters	
auxiliary power unit erosion, inlet filter clogging with sand after 5 hours (Desert Storm)	new inlet particle separator rapidly designed, manufactured and distributed
Helicopters operating in the Kuwaiti theater during Desert Storm	
wind-blown sand eroded rotor blade protective coating and paint	additional maintenance actions, change in blade coating material

Table VIb
UNANTICIPATED CHARACTERISTICS DISCOVERED IN SERVICE

CHARACTERISTIC	CONSEQUENCE
F-16 Fighting Falcon fighter-bomber	
structural cracks in wing carry-through bulkheads and other areas at less than 1/4 of expected airframe life	grounded many aircraft, ultimate correction unknown, modification or scrapping of aircraft
F-16C/D susceptible to deep stalls and departure from controlled flight, fleet accidents	additional flight testing, revised flight control system software
F-16C heavy pitch oscillation (different configurations than documented in flight test)	flight manual restrictions, additional flight testing
oscillation of heavy under-wing stores	sets carriage limits
engine failures and aircraft losses due to cracks in turbine seal, other durability problems	many aircraft grounded, modification to seal, other changes for other problems
F-15 Eagle fighter	
nose gear shimmy developed after a few years of operation due to wear and freeplay in components	revised maintenance procedures
wing rock and susceptibility for departures from controlled flight experienced at some conditions	changed stabilator rigging and functional check flight procedures, additional flight testing
F-15E Strike Eagle fighter-bomber	no departure and spin testing on F-15E because analysis suggested no change from baseline F-15
unacceptable spin susceptibility, departures from controlled flight experienced, two aircraft lost	limits imposed by user, revisions to flight control software and cockpit warnings, additional testing
high cycle fatigue failures cracks in engine fan blades, other durability problems, operational impact	additional ground and flight testing, additional analysis, fleet-wide engine modifications
long term avionics reliability concerns with high operating temperatures, insufficient cooling on ground	rapidly manufactured and shipped ducts to allow two cooling carts to provide air to avionics (Desert Storm)
F-14A Tomcat fighter	
tendency for engine compressor stall during aggressive maneuvering or low airspeed inlet blanking, crashes	additional training awareness, program to install digital flight control system and inlet pressure indicator
departure from controlled flight with asymmetric thrust and external stores, aircraft lost	additional flight testing to determine characteristics and recommend changes to training program
F-18 Hornet fighter-bomber	
more frequent conversions to the mechanical flight control system modes than anticipated	additional flight testing to determine mechanical system characteristics (little done in initial program)
numerous flight control deficiencies in mechanical flight control modes	unspecified system changes
spin susceptibility, fleet losses	additional flight testing, revised flight control system software and training procedures
Aircraft windscreens, sensor windows and lenses during Desert Storm	
damage from sand erosion, degraded performance	special coatings rapidly developed and deployed, special maintenance procedures for buffing surfaces

Table VII
COMPARISON OF FLIGHT TESTING REQUIREMENTS

C-5A Galaxy airlifter (1968)	
56 months, 5 aircraft, 3,939 flight hours	
B-1A bomber (1974)	
planned 52 month, 4 aircraft, terminated about half way at 1,891 flight hours	
F/A-18 Hornet fighter-bomber (1978)	
41 months (basic development and operational testing), 12 aircraft, 5,026 flight hours	full electronic warfare suite tested later, unknown time or flight hours
B-2A bomber (1989)	very cautious test program because of unique features, great expense of vehicles, and risk to program
7 aircraft, 8 yr development test, 4,870 flight hrs, all flight testing to end in middle of year 2000	flight testing includes C-135 avionics testbed with >1600 flight hours
C-17A Globemaster airlifter (1991)	mostly proven technology, but first high-gain flight control on large aircraft, fast paced flight test program
39 months, 6 aircraft (135 aircraft-months), 4,300 flight hours	initially planned as 70 aircraft-month program, mostly problems with aircraft required extension
V-22A Osprey tilt-rotor tactical transport (1992)	(flight test in progress)
EMD planned for late 1996 through mid 1999, followed by OPEVAL, 4 aircraft, 1,605 flight hours	FSD and Risk Reduction flight testing since mid 1989 included about 1,000 flight hours on 5 aircraft
F-22A Fighter (1997)	(flight test yet to begin)
planned for 60 months, 5,500 flight hours, 13 aircraft	
777 airliner (1994)	to full certification of first aircraft with one engine type
5 aircraft, 2,840 flights, 3,619 flight hrs, 4,376 ground test hrs, 15.9 months, including ETOPS testing	earlier 767 was 5 aircraft, 1,584 flights, 1,793 flight hrs, 667 ground test hrs, 10 months
B-1B Lancer bomber (1984)	*Revised Design*, initial design (B-1A) never fully developed, substantial changed for B-1B
81 months, 5 aircraft, 3,169 flight hours	
MD-11 airliner (1990)	*Revised Design*, very fast-paced flight test program for certification and to make first delivery date
5 aircraft, 10 months	
MD-90 airliner (1993)	*Revised Design*, derivative design with new engines and revised cockpit
20 month program, 1,900 flight hours, 1,460 flights, some additional testing to solve unexpected problems	originally planned as 12 month program, adopted leisurely pace because no immediate customers
F/A-18E/F fighter-bomber (1996)	*Revised Design*, considerable redesign of existing aircraft (flight test in progress)
planned 3 year test program with 7 aircraft, 2,000 flights, average 15 flights per month	believe shorter than for all new design, saved 8-10 months through careful planning and coordination
C-130J airlifter (1996)	*Revised Design* (flight test in progress)
8 aircraft, about 1,400 flight hours planned	three aircraft added during testing to make up for delays

SOURCES

Table Ia

Coulam, R.F., "Illusions of Choice: The F-111 and the Problem of Weapons Acquisition Reform" Princeton, New Jersey, Princeton University Press, 1977.

Norton, W.J., Capt, USAF, "Limit Cycle Oscillations and Flight Flutter Testing," *in* "Proceedings of the 21st Annual Symposium of the Society of Flight Test Engineers", August 1990, pp 3.4-1 to 3.4-12.

Rice, B., "The C-5A Scandal: An Inside Story of the Military-Industrial Complex", Boston, Massachusetts, Houghton Mifflin Company, 1971.

Stevenson, J.P., "The Pentagon Paradox: The Development of the F-18 Hornet", Maryland, USA, Naval Institute Press, 1993.

Discussions with participants.

Table Ib

Farley, H.C., Jr., "F-117A Flight Test Program", *in* "34th Symposium Proceedings of the Society of Experimental Test Pilots", 1990, pp 141-167.

Scott, W.B., "B-1B Stability Enhancement Tests Verify Low-Level Mission Capability", Aviation Week & Space Technology, 26 June 1989, pp 34-35.

Silz, R., "An Overview of the F-117A Avionics Flight Test Program", *in* "Proceedings of the 23rd Annual Symposium of the Society of Flight Test Engineers", August 1992, pp 1-46 to 1-56.

"Air Force Starting Flight Tests of B-1B Defense Avionics System", Aviation Week & Space Technology, 15 October 1990, pp 50-51.

Table IIa

Mortensen, J.A., Maj, USMC and Cricchi, S., "U.S. Navy T-45A Departure and Spin Evaluation", *in* "39th Symposium Proceedings of the Society of Experimental Test Pilots", September 1995, pp 114-131.

Nordwall, B.D., "Tests Prove T-45 Flight Controls Are Suitable for Carrier Use", Aviation Week & Space Technology, 25 February 1991, pp 38-41.

North, D.M., "T-45 Stable Platform for Advanced Training", "Long Development Phase Nearly Over for Goshawk", and "McDonnell Douglas Provides Logistical Support for T-45," Aviation Week & Space Technology, 30 August 1993, pp 36-43.

Pence, R.A., "T-45A Goshawk Full Scale Development Flight Test Program Overview", *in* "Proceedings of the 23rd Annual Symposium of the Society of Flight Test Engineers", August 1992, pp 1-65 to 1-76.

"Boeing Modifies E-6A Prototype", Aviation Week & Space Technology, 5 May 1991.

"T-46A Trainer Testing Accelerates Despite USAF Bid to Cancel Program", Aviation Week & Space Technology, 24 March 1986, pp. 66-67.

Norton, W.J. Capt., "Structures Flight Test Handbook", AFFTC-TIH-90-001, November 1990, pp. 6-4.

Table IIb

Hopkins, R.C. and Blazer, R., "V-22 Flight Test", *in* "34th Symposium Proceedings of the Society of Experimental Test Pilots", 1990, pp 67-81.

LeVoci, P.A., CDR, USN and Macdonald, T.L., "V-22 Osprey Flight Test Update", *in* "38th Symposium Proceedings of the Society of Experimental Test Pilots", September 1994, pp 4-22.

Linn, K., Dunford, P.J. and Sullivan, P., "V-22 Tiltrotor Development & Flight Characteristics", *in* "Proceedings of the 23rd Annual Symposium of the Society of Flight Test Engineers", August 1992, pp 1-77 to 1-90.

Morrocco, J.D., "V-22 Strakes to Counter Empennage Buffeting", Aviation Week & Space Technology, 22 August 1994, pp 26.

Smith, G., "Flight Test Activities - C-130J", report to the AIAA Flight Test Technical Committee, February 1996.

"C-130J Software Problems Addressed", Aviation Week & Space Technology, 5 February 1996, pp 28.

Statements made by McDonnell Douglas chief test pilot to visitors from the Society of Experimental Test Pilots Symposium at the Douglas Aircraft plant, Long Beach, California, September 1995.

Table III

Birk, F.T., Col, USAF and Staley, C.W., "B-2A Flight Test Update", *in* "36th Symposium Proceedings of the Society of Experimental Test Pilots", September 1992, pp 174-187.

Cameron, S.E., Lt Col, USAF and Crenshaw, K., "B-2 Safety Lessons Learned", *in* "39th Symposium Proceedings of the Society of Experimental Test Pilots", September 1995, pp 208-223.

Dunn, J.C., Col, USAF and Weiss, D.L., "B-2A Flight Test Progress Report", *in* "39th Symposium Proceedings of the Society of Experimental Test Pilots", September 1995, pp 17-33.

Gilmartin, P.A., "Senate Tightens B-2 Restrictions in Wake of Stealth Testing Dispute", Aviation Week & Space Technology, 23 September 1991, pp 25.

Morrocco, J.D., "Air Force Prepares to Operate B-2 Bomber", Aviation Week & Space Technology, 13/20 December 1993, pp 29.

Nordwall, B.D., "B-2 Radar Begins Low-Level Tests", Aviation Week & Space Technology, 16 October 1995, pp 55-56.

Scott, W.B., "Air Force Weighs Several Options for Improving B-2 Stealth Qualities", Aviation Week & Space Technology, 11 November 1991, pp 80.

"Air Force Discovers Structural Problems in Titanium Aft Deck of B-2 Bomber", Aviation Week & Space Technology, 23 April 1990, pp 34.

"No. 1 B-2 Completes First Round of Low Observables Testing", Aviation Week & Space Technology, 26 November 1990, pp 30.

"Flight Testing, Lab Simulation Prompt Changes that Improve B-2 Capability", Aviation Week & Space Technology, 4 February 1991, pp 51.

"GAO Says Initial Tests Confirm B-2's Ability to Evade Radar", Aviation Week & Space Technology, 6 May 1991, pp 66.

"Fifth B-2 Joins USAF Test Fleet", Aviation Week & Space Technology, 12 October 1992, pp 54.

Table IV

Norris, G', "Mighty Moose," Flight International, 30 August - 5 September 1995, pp 28-29.

Norton, W.J. Capt, USAF, "C-17A Landing Gear Shimmy Testing", *in* "Proceedings of the 24th Annual Symposium of the Society of Flight Test Engineers", July 1993, pp 6-39 to 6-53.

Norton, W.J. Maj, USAF and Melroy, P.A, Maj, USAF, "C-17A Airloads Flight Tests", *in* "38th Symposium Proceedings of the Society of Experimental Test Pilots", September 1994, pp 176-204.

Norton, W.J., Capt, USAF, "Aeroelastic Pilot-in-the-Loop Oscillations", AGARD-AR-335, February 1995.

Peron, L.R. and Cloughley, D.C., "Techniques for the Evaluation of Handling Qualities and Pilot-in-the-Loop Oscillation Susceptibility During the Flight Test of the C-17A Aircraft", *in* "Proceedings of the 26th Annual Symposium of the Society of Flight Test Engineers", 19-23 June 1995, pp 4-39 to 4-50.

Smith, B.A., "C-17 Payload-Range Spec Called Outdated", Aviation Week & Space Technology, 15 February 1993, pp 66.

Smith, B.A., "C-17 Flight Tests Assess Aerodynamics", Aviation Week & Space Technology, 15 February 1993, pp 66.

Smith, B.A., "Flight Test Pace for C-17 Under Review", Aviation Week & Space Technology, 26 April 1993, pp 20-21.

Smith, B.A., "C-17 Close to Operational Status", Aviation Week & Space Technology, 5 September 1994, pp 115-117.

Vadnais, S., Capt, USAF, "Jump Start," Leading Edge, June 1995, pp 20.

"C-17 Test Pilots Report Flight Control Problems", Aviation Week & Space Technology, 12 October 1992, pp 51.

"C-17 Yuma Drop Tests", Aviation Week & Space Technology, 3 April 1995, pp 77.

"C-17 Gains Clearance for Paratrooper Testing", Aviation Week & Space Technology, 8 May 1995, pp 22-23.

Personal knowledge gained as a lead engineer on the flight testing of the C-17.

Table V

Cashman, J.E., "Boeing 777 - Progress to the Plan", *in* "39th Symposium Proceedings of the Society of Experimental Test Pilots", September 1995, pp 4-16.

Dornheim, M.A., "Boeing Corrects Several 777 PIOs", Aviation Week & Space Technology, 8 May 1995, pp 32.

Floyd, D.A., "Boeing 777-200 Flight Test Progress Report," *in* "Proceedings of the 26th Annual Symposium of the Society of Flight Test Engineers", 19-23 June 1995, pp 2-1 to 2-12.

Kanebo, S.W., "First GE-Powered 777 Will Be Late", Aviation Week & Space Technology, 2 October 1995, pp 31.

Proctor, P., "Boeing Expands 777 Program with Second Flight Test Aircraft", Aviation Week & Space Technology, 25 July 1994, pp 34-35.

Proctor, P., "Boeing Begins 777 Certification Tests", Aviation Week & Space Technology, 12 September 1994, pp 33.

Aviation Week & Space Technology, 23 October 1995, pp 21.

Statement of high level 777 team member and Boeing official before the ITEA Symposium in Huntsville, Alabama, 1995.

Table VIa

Bond, D.F., "USAF Grounds Some B-1B Bombers, Strengthens Cracking Longerons", Aviation Week & Space Technology, 12 August 1991, pp 45.

Fulghum, D.A., "U.S. Army Aviation to Assume Frontline Role in Saudi Arabia", Aviation Week & Space Technology, 15 October 1990, pp 80.

Kanebo, S.W., "Sand Ingestion Problem Prompt U.S. Army to Modify Transport/Utility Helicopters", Aviation Week & Space Technology, 11 March 1991, pp 21.

Hughes, D., "Design, Checks cited in Crash", Aviation Week & Space Technology, 1 November 1993, pp 39.

Phillips, E.H., "Wing Slat Control Cited in Chinese MD-11 Accident", Aviation Week & Space Technology, 8 November 1993, pp 37-38.

Phillips, E.H., "ATR42/72 Review Focuses on Icing," Aviation Week & Space Technology, 14 November 1994, pp 28.

Philips, E.H., "FAA Orders L-1011 Fatigue Crack Checks", Aviation Week & Space Technology, 29 May 1995, pp 33.

Scott. W.B., "MD-11 Flight Testing Progresses Toward End-of-Year Certification", Aviation Week & Space Technology, 4 June 1990, pp 19.

Smith, B.A., "Engine Maker and Douglas Work to Improve MD-11 Range", Aviation Week & Space Technology, 6 August 1990, pp 70-71,

Smith, B.A., "Singapore Airlines Drops MD-11 As Douglas Plans Modifications", Aviation Week & Space Technology, 5 August 1991, pp 25.

West, A. and Ludlam, J. "Development of an Interim Engine Inlet Barrier Filter Mission Kit", presented at the 23rd Annual Symposium of the Society of Flight Test Engineers, August 1992.

Velocci, A.L., Jr., and McKenna, J.T., "MD-11 Deliveries Crucial to Company's Finances", Aviation Week & Space Technology, 15 July 1991, pp 34.

"737 Survives Major Damage", Flight International, 7 May 1988, pp 2.
"USAF, LTV Probe Wing Cracks that Grounded Air Guard A-7s", Aviation Week & Space Technology, 29 May 1989, pp 29.
"C-141 Wing Crack Inspections Continue", Aviation Week & Space Technology, 22 January 1990, pp 30.
"Engine Modifications, Inspections Allow Air Force to Return B-1Bs to Flight Status", Aviation Week & Space Technology, 11 February 1991, pp 24.
"Crandal Criticizes McDonnell Douglas, Unspecified Problems with MD-11 Transport," Aviation Week & Space Technology, 29 February 1991, pp 29.
"Douglas, Key Customers Work to Solve Early MD-11 Problems", Aviation Week & Space Technology, 4 March 1991, pp 30-32.
"Sikorsky Delivers Inlet Particle Separators for Black Hawk APUs", Aviation Week & Space Technology, 1 April 1991, pp 26.
"American Begins MD-11 Service After Resolution of Performance Shortfalls", Aviation Week & Space Technology, 6 May 1991, pp 29.
"MD-11 Fuel Tank Changes Boost Long-Range Payload", Aviation Week & Space Technology, 21 October 1991, pp 32.
"ATR Flight Tests New Deicer", Aviation Week & Space Technology, 23 January 1995, pp 47.
"Rain Erodes B-2 Paint", Aviation Week & Space Technology, 13 February 1995, pp 57.
"Boeing to Reinforce 757, 767 Pylons", Aviation Week & Space Technology, 22 May 1995, pp 30.
"United Crews Note 'Tail Wag' in 777", Aviation Week & Space Technology, 2 October 1995, pp 31.
"Boeing Tackles 'Tail-Wag' Problem on United 777s", Flight International, 6-12 December 1995, pp 10.

Table VIb

Conigliaro, P. and Stiles, H.W., "F-14A Low-Altitude Asymmetric Thrust Simulation and Flight Test Program", *in* "16th Annual Symposium Proceedings of the Society of Flight Test Engineers", August 1985, pp 2.5-1 to 2.5-6.
Edwards, B.S. and Sample, D.L., "Is There a Shimmy in your Eagle's Nosegear?", Product Support Digest, McDonnell Douglas Corporation, date unknown, pp 2-3.
Felock, J., Maj, USAF, Habig, C., Maj, USAF and Hancock, R., Maj, USAF, "Keep Eagle: F-15E High Angle of Attack Testing", in "39th Symposium Proceedings of the Society of Experimental Test Pilots", September 1995, pp 180-191.
Flynn, W.A., Maj, CAF and Fergione, J., "F-16 Digital Flight Control System Improvements", *in* "36th Symposium Proceedings of the Society of Experimental Test Pilots", September 1992, pp 165-173.
Fulghum, D.A., "Desert Storm Success Renews USAF Interest in Specialty Weapons", Aviation Week & Space Technology, 13 May 1991, pp 85.
Kanebo, S.W., "U.S. Air Force Grounds Pratt F100 IPEs Shortly After Korea Selects Powerplant", Aviation Week & Space Technology, 2 September 1991, pp 27.
Keller, K.L., Janzen, D.B. and Asay, A.A., "Utility of Ground Simulation in Flight Control Problem Identification, Solution Development and Verification," in "AGARD Conference Proceedings 513", November 1993, pp 3-1 to 3-8.
Kernstock, N.C. "U.S. Marine Harrier Units Maintain Brisk Flight Schedule in Desert", Aviation Week & Space Technology, 1 October 1990, pp 104.
Norton, W.J, Capt, USAF, "Limit Cycle Oscillation and Flight Flutter Testing", *in* "21st Annual Symposium Proceedings of the Society of Flight Test Engineers" August 1990, pp 3.4-1 to 3.4-12.
Praters, D.L., Lt, USN, Stevens, M.G. and Lackey, J.B., "F/A-18 Controls Released Departure Recovery Flight Test Evaluation", *in* "36th Symposium Proceedings of the Society of Experimental Test Pilots", September 1992, pp 77-96.
Scott, W.B., "Navy Grounds 8 Top Gun F-16s Due to Cracks", Aviation Week & Space Technology, 24 May 1991, pp 24.
Scott, W.B., "Structural Cracking in F-16s Reveals Philosophical Divide Between Services", Aviation Week & Space Technology, 5 August 1991, pp 53.
Snyder, B., Capt, USAF, Watrous, D., Maj, USAF and Walker, L.A., "Operational Improvements to the Eagle's High Angle of Attack Handling Qualities", *in* "38th Symposium Proceedings of the Society of Experimental Test Pilots", September 1994, pp 237-252.
Stevens, M.G., "F/A-18 Digital Flight Control System Degraded Modes Flight Evaluation", *in* "20th Annual Symposium Proceedings of the Society of Flight Test Engineers", September 1989, pp 6.2-1 to 6.2-12.
"F-16C/D High Angle of Attack Instability Overcome by Flight Control Modifications", Aviation Week & Space Technology, 13 November 1989, pp 61.
"Program Offers Rapid Solution to Problems Encountered by F-15Es Engaged in Gulf War", Aviation Week & Space Technology, 4 February 1991, pp 59.
"U.S. Air Force to Modify or Scrap All Existing F-16s Due to Structural Cracks", Aviation Week & Space Technology, 29 July 1991, pp 22.
"USAF, GE Develop F110 Engine Plan", Aviation Week & Space Technology, 12/19 December 1994, pp 22.
"Accidents Prompt F-14 Upgrade", Flight International, 13-19 March 1996, pp 5.

Table VII

Cashman, J.E., "Boeing 777 - Progress to the Plan", in "39th Symposium Proceedings of the Society of Experimental Test Pilots, September 1995", pp 4-16.
Dunn, J.C., Col, USAF and Weiss, D.L., "B-2A Flight Test Progress Report", in "39th Symposium

Proceedings of the Society of Experimental Test Pilots", September 1995, pp 17-33.

Floyd, D.A., "Boeing 777-200 Flight Test Progress Report", in "Proceedings of the 26th Annual Symposium of the Society of Flight Test Engineers", 19-23 June 1995, pp 2-1 to 2-12.

Hart, R.E. and Rawlings, K., III, "B-2 Flight Test Program - Where Are We?", *in* Proceedings of the 26th Annual Symposium of the Society of Flight Test Engineers, 19-23 June 1995, pp 2-13 to 2-15.

Kanebo, S.W., "Innovations to Boost F-22 Flight Test Efficiency", Aviation Week & Space Technology, 12 June 1995, pp 92-96.

Kanebo, S.W., "New Hornet Rolls Out on Time, Within Budget," Aviation Week & Space Technology, 25 September 1995, pp 90-92.

LeVoci, P.A., CDR, USN and Macdonald, T.L., "V-22 Osprey Flight Test Update", *in* "38th Symposium Proceedings of the Society of Experimental Test Pilots", September 1994, pp 4-22.

Proctor, P., "Early Modeling Helps Speed 777 Flight Testing", Aviation Week & Space Technology, 12 June 1995, pp 124 & 133.

Scott, W.B. "New Global Pressures Reshape Flight Testing", Aviation Week & Space Technology, 12 June 1995, pp 62-65 and Aviation Week & Space Technology, 3 June 1996, p. 25.

Smith, B.A., "Reduced Defense Funding Drives Management Changes", Aviation Week & Space Technology, 12 June 1995, pp 97- 98.

Smith, G., "Flight Test Activities - C-130J", report to the AIAA Flight Test Technical Committee, February 1996.

Statements made by McDonnell Douglas chief test pilot to visitors from the Society of Experimental Test Pilots Symposium at the Douglas Aircraft plant, Long Beach, California, September 1995.

Performance and Guidance System Testing using Differential GPS on a Falcon 20 Aircraft

John B. Croll
Research Test Pilot
CNRC
Ottawa, Ontario
Canada K1A 0R6

1.0 SUMMARY

Using a Falcon 20 research aircraft, a program was conducted at the Canadian National Research Council (CNRC) to investigate the use of a differential Global Positioning System (GPS) to 1) provide aircraft guidance on precision instrument approaches, and 2) measure aircraft performance parameters during typical flight test manoeuvres needed for aircraft certification. The initial series of tests used a differential GPS with NovAtel 951R receivers installed in the aircraft and at the ground station, and with a VHF radio link to provide real-time differential corrections. This system fell slightly short of the vertical accuracy criteria needed for precision approaches to Category I limits, and did not meet the accuracy criteria desired for flight test measurement.

Following an upgrade to a NovAtel RT-20™ differential GPS, a program was conducted to determine the landing performance of the Falcon 20 on winter contaminated runways (covered with ice or snow). The real-time position and height accuracies of the upgraded system were determined to be less than 20 centimeters, falling well within the accuracy criteria for Category I approaches, and enabling this system to be used as the primary device for measuring aircraft landing distances from a height of 50 feet (15 meters) to a complete stop. During this program, a strong correlation was found between aircraft deceleration during full braking and the runway friction index reported by a ground test vehicle, allowing the aircraft landing distance to be accurately predicted as a function of the runway friction index.

2.0 INTRODUCTION

The CNRC Falcon 20 aircraft was acquired from the Canadian Forces in 1991 and converted to a research configuration for two main purposes; 1) to support the Canadian Space Agency as a microgravity research vehicle and 2) to support the Transport Canada Microwave Landing System (MLS) program as a vehicle for the development and demonstration of curved, segmented precision approaches. Modifications were made to the aircraft fuel and hydraulic systems for the zero gravity environment, and the aircraft remains a viable microgravity testbed today. A data acquisition and computing system was developed to provide aircraft positioning and guidance for the curved approaches, and with the cancellation of the MLS program in North America, this system was easily converted to permit the use of the GPS as an aircraft position sensor.

For aircraft precision approaches to at least Category I decision height limits of 200 feet (61 meters), a differential GPS (DGPS) with a real-time position and height accuracy in the order of one meter was desirable. If this degree of position accuracy could be achieved during the execution of an instrument approach, it was evident that the DGPS could also be used for the measurement of aircraft position, and perhaps velocity and acceleration, for flight test work, either experimental or for aircraft certification. This paper describes the initial DGPS installed in the CNRC Falcon 20, it's integration with the aircraft avionics systems to provide guidance to Category I approach limits, and it's accuracy and application as a flight test measurement tool. The improved accuracy resulting from the installation of an upgraded DGPS will be described, and the results of aircraft landing performance tests on winter contaminated runways using this system will be presented.

3.0 EQUIPMENT DESCRIPTION

3.1 Falcon 20 Research Aircraft

The CNRC Falcon 20, C-FIGD, shown in Figure 1, is a business jet designed and built by Avions Marcel Dassault. The aircraft is powered by two General Electric model CF700-2D2 turbofan engines. Conventional flight control surfaces are actuated by two independent hydraulic systems, and pitch trim is accomplished by electrically operated control of the horizontal stabilizer. The aircraft operating speeds are normally in the Category "C" range (121 to 140 knots) for precision instrument approaches. A Sperry SPZ 500 integrated flight control system (IFCS) is available to fly either manual or coupled precision approaches using the normal Instrument Landing System (ILS) or the experimental DGPS. The main components of the IFCS are the pilot's and co-pilot's attitude director indicators (ADI), horizontal situation indicators (HSI), flight director computers (FDC) and mode selectors, and the single autopilot computer and controller.

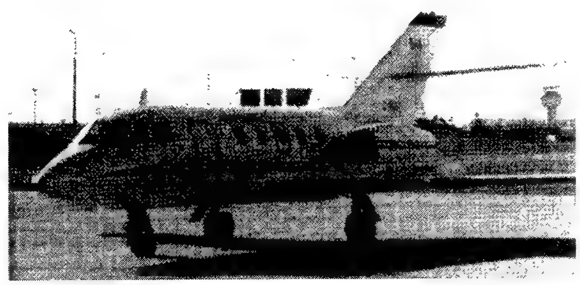


Figure 1
The CNRC Falcon 20 Research Aircraft

The Falcon 20 had an onboard data acquisition system (DAS) in a standard 19 inch avionics rack mounted on the seat rails in the rear cabin of the aircraft. The rack was modular in the sense that certain components of the DAS, or the entire rack, could be easily removed from the aircraft for maintenance or bench testing. The DAS included all interfaces for the following specially mounted instrumentation sensors:

a. Pitot and static pressure transducers and total temperature probe;
b. Five pressure ports on the aircraft nosecone with transducers for angle of attack and angle of sideslip measurement;

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

c. Weight on wheels and brake pressure transducers;
d. Accelerometers and rate gyros in all three axes;
e. Pitch, roll and heading sensors; and
f. Radar altimeter.

The DAS was integrated with the aircraft GPS receiver and other aircraft navigation systems through standard digital interfaces, and with the pilot's and co-pilot's flight instruments through the navigation and FDC junction boxes. A Digital Equipment Corporation LSI 11/73 was used as a central processing unit (CPU) to translate the real-time DGPS position and height information into an x,y,z coordinate system referenced to the runway Glide Path Intercept (GPI) point. This aircraft position was compared to the approach path selected by the pilot on a control and display unit (CDU) in the cockpit to determine the lateral and vertical track deviations. These deviations, along with additional computed approach information such as course and distance to go to touchdown, were sent to the Sperry IFCS for approach steering using the cockpit flight instruments.

An equipment rack and project operator's station were located in the aircraft cabin forward of the DAS. The rack contained the DGPS equipment which will be described in the next section. The operator's station was used to initialize and control the airborne software program, and to troubleshoot the DAS when required. The DAS included a digital audio tape (DAT) with a 1.2 gigabyte capacity, which was used as a recording medium for the DGPS information, approach guidance parameters and other aircraft data (angles, rates, accelerations). The recording rate was set at 8 Hz.

3.2 Differential GPS Equipment

Figure 2 shows a block diagram of the DGPS setup. The initial GPS receiver installed in the Falcon 20 was a NovAtel 951R single frequency (L1=1575.42 MHz) ten channel receiver. Rather than being a self-contained unit, this was a receiver card installed in a Dell 486 computer and connected to an antenna on top of the aircraft. A second identical receiver card was installed in a computer at the ground station, and connected to an antenna whose exact position had been surveyed by standard control survey techniques. With both receivers running at the same time and referenced to the same satellite vehicle (SV) constellation, the ground station position and height corrections were applied to the airborne system, providing a basic DGPS system. For real time corrections, a VHF data link provided updates from the ground station every two seconds on an assigned frequency of 172.725 MHz. Post-flight solutions for aircraft position and height were also determined to a very high degree of accuracy by using a program to resolve the carrier phase ambiguities to within one carrier wavelength of about 19 cm. Real-time DGPS data was updated at 5 Hz, while data for post-flight processing was updated at 1 Hz.

In order to determine the accuracy of the NovAtel DGPS during approaches and flight test manoeuvres, a second DGPS was used as a positional "truth" system. Shown in Figure 2 along with the NovAtel DGPS, this system included two Ashtech Z-12 dual frequency 12 channel GPS receivers, one in the aircraft and one at the ground station. The Ashtech DGPS system was not used in the real-time mode, but processed post-flight to a solution with full carrier phase ambiguity resolution. As such, it qualified as a Time Space Position Information System (TSPI), according to tests conducted on an identical system at the FAA Technical Center in Atlantic City, NJ (Reference 1), which showed the Ashtech Z-12 DGPS to be more accurate than two different configurations of laser trackers. For this reason, the Ashtech DGPS was used as a stand-alone "truth" system, without reference to additional systems, other than the occasional visual confirmation of the aircraft position on the runway with respect to the GPI point.

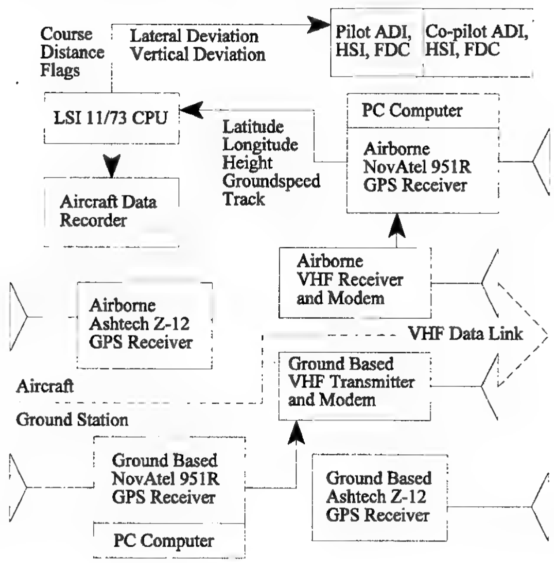


Figure 2
Falcon 20 Differential GPS System Setup

4.0 GUIDANCE SYSTEM TESTING

The NovAtel DGPS guidance system was tested to determine its Total System Error (TSE) during the conduct of straight-in precision approaches to Category I limits. The TSE was the root-sum-square of the Navigation System Errors (NSE), or the differences between the DGPS derived aircraft position (real-time) and the true aircraft position, and the Flight Technical Errors (FTE), or the pilot/autopilot errors in flying the approach commanded by the guidance system. TSE is related to FTE and NSE by the formula:

$$TSE = \sqrt{FTE^2 + NSE^2} \tag{1}$$

The flight tests consisted of three separate flights used to fly a total of 24 approaches to the Ottawa International Airport, Runway 25, where there was no equivalent ILS precision approach. Standard left or right hand patterns were flown for each approach, with an intercept angle of about 30 degrees to the final approach segment. The final approach segment was 5 to 6 nautical miles (nm) long, and descended along a 3 degree glidepath, intercepting the runway surface at approximately 1000 feet (300 meters) from the threshold. Two or more approaches on each flight were flown coupled to the aircraft autopilot, with the remainder manually flown using the Sperry SPZ-500 flight director. The approaches were all flown as closely as possible to the intended approach path down to Category I limits, after which the pilot took over visually for the remainder of the descent profile to the runway. Most of the approaches were terminated with a touch-and-go on the runway; two were low approaches and three were full stop landings.

Figure 3 shows the cross-track deviation (CTD), in feet, plotted against the along-track distance (ATD), in nautical miles, for all 24 approaches. The ATD was the computed horizontal distance, along the approach track, from the aircraft position to the GPI point. The approaches progress from right to left in Figure 3, with the pilot taking over visually at an ATD of 0.5 nautical miles. The solid lines converging towards the approach path from either side depict the standard full scale (two dot) lateral deviation limits on

the pilot's HSI, beyond which the pilot would have to break off the approach due to a failure to meet obstacle clearance criteria. These deviation limits decrease with decreasing ATD, resulting in an increasing steering sensitivity over the last 4.5 nautical miles of the approach. This effect can be seen by the gradual decrease in CTD as the approaches progress towards the GPI point. For all approaches, the achieved CTD can be seen to be well within the full scale limits.

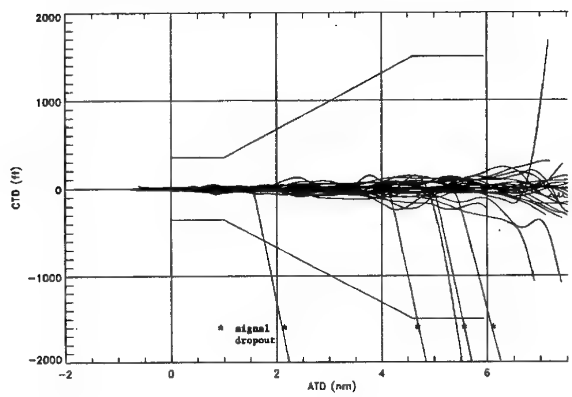


Figure 3
Cross-track Deviation versus ATD, using DGPS Guidance

Figure 4 shows the vertical-track deviation (VTD), in feet, plotted against ATD, in nautical miles, for all 24 approaches. All of the intercepts, except one, were from below the glidepath. Full scale vertical deviation limits are also shown in Figure 4, with the achieved VTD well within these limits. Following aircraft touchdown at an ATD of about 0.0, the VTD increases because the theoretical glidepath extends below the runway surface at a 3 degree angle.

The DGPS signal dropouts shown in Figures 3 and 4 occurred four times over the course of the 24 approaches. These dropouts caused a momentary full scale deflection of the instruments being used to fly the approach, distracting the pilot, but not causing the approach to be aborted. A GPS dropout test was added to the Falcon airborne software program following these tests to maintain continuity of data on the flight instruments, while allowing the dropouts to be recorded for future investigation.

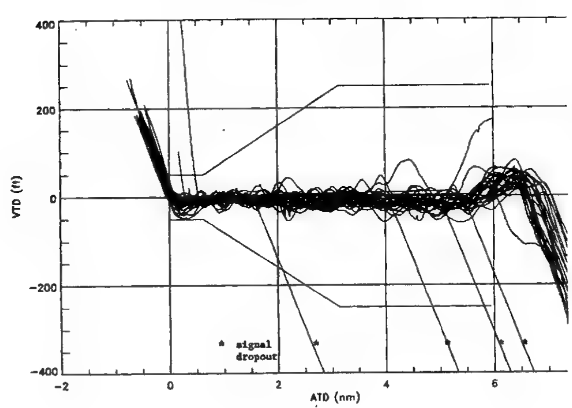


Figure 4
Vertical-track Deviation versus ATD, using DGPS Guidance

The FTE and NSE are each determined to a 95% confidence level by adding the absolute value of the mean error to twice the value of the standard deviation (sigma). For the FTE, these values are calculated from the deviations shown in Figures 3 and 4 at an ATD between 0.5 and 0.6 nautical miles, equivalent to a decision height of 200 feet (61 meters). As shown in Table 1, the lateral FTE is 12.3 meters and the vertical FTE is 7.4 meters. Analysis of the NovAtel 951R real-time DGPS position and height versus the Ashtech Z-12 TSPI post-flight processed solution for the 24 approaches resulted in lateral and vertical NSE's of 6.5 meters and 8.2 meters respectively. The TSE's shown in Table 1 are computed from Equation 1. In order to meet the required navigation performance (RNP) criteria being introduced by the FAA (Reference 2), an aircraft must pass through an inner "tunnel," whose dimensions vary with height above touchdown, within a 95% confidence level. At a height of 200 feet (61 meters), the tunnel halfwidths, or total system error (TSE) requirements are ±33.5 meters laterally and ±9.8 meters vertically.

	Lateral Errors (meters)		
	Mean	Sigma	*Mean* + 2 Sigma
FTE	-1.3	5.5	12.3
NSE	0.9	2.8	6.5
TSE	-	-	13.9
RNP	-	-	33.5
	Vertical Errors (meters)		
	Mean	Sigma	*Mean* + 2 Sigma
FTE	-2.2	2.6	7.4
NSE	0.2	4.0	8.2
TSE	-	-	11.1
RNP	-	-	9.8

Table 1
Summary of Errors - DGPS Category I Approaches

Table 1 shows that the lateral system errors were within the RNP for Category 1 precision approaches, and even within the more stringent RNP for higher category approaches, which are ±23 meters at 100 feet (30 meters) height, and ±15.5 meters at 50 feet (15 meters) height. The vertical system errors, however, did not quite meet the RNP criteria for Category I approaches. The reasons for this were twofold. First, a mean vertical FTE of -2.2 meters occurred consistently during the approaches due to a calibration error in the aircraft flight director. Second, the large standard deviation of 4.0 meters for the NovAtel DGPS height error resulted in an unusually large NSE for the system under test. This was influenced to some extent by a non-standard configuration of the NovAtel ground station GPS antenna, which made it more susceptible to multi-path effects. Correction of either one of these error sources, especially the NSE, would have brought the vertical TSE to within the RNP criteria for Category I approaches. The concept of using DGPS guidance to fly precision approaches was well demonstrated during these tests, but a more accurate system was required to determine the aircraft height above the runway.

5.0 FLIGHT TEST MEASUREMENT

The application of the Falcon 20 NovAtel DGPS as a flight test measurement tool was explored during the same time period, and with the same DGPS configuration, as the precision approach testing described above. The objectives of the tests were to demonstrate DGPS based measurement techniques in collecting

aircraft performance data during certification type flight test manoeuvres, and to determine the NovAtel 951R receiver based DGPS position and height accuracies, both real-time and post-flight processed, in comparison with the Ashtech Z-12 TSPI. Among the test points conducted were:

a. Airfield performance manoeuvres including maximum power takeoffs, simulated single engine takeoffs, a rejected takeoff from V_1, performance landings, and a simulated V_{mcg} ground run;
b. Autopilot performance tests to include simulated autopilot malfunctions on an ILS or MLS glidepath, and simulated autopilot touchdown accuracies;
c. Flight performance manoeuvres to include airspeed calibration runs and climb profiles; and
d. Community noise tests to include low altitude fly-bys and intercepts of the fly-by profile from a normal takeoff.

5.1 DGPS Accuracies

Table 2 shows the results of the accuracy tests, with the real-time errors being the differences between the NovAtel real-time DGPS solution and the Ashtech TSPI solution, and the Carrier Phase Ambiguity Resolution (CPAR) errors being the differences between the NovAtel DGPS post-flight processed solution with full CPAR and the Ashtech TSPI. As noted earlier, the Ashtech TSPI solution always included full CPAR. Since most flight test manoeuvres are measured from one position relative to another, only the "2 sigma" errors are shown in Table 2, as opposed to the absolute errors (*mean* + 2 sigma).

	Horizontal Errors (2 Sigma)	
	Real-time (m)	CPAR (m)
Takeoffs	1.5	0.02
Landings	0.68	0.02
Climbs	1.4	0.08
Airspeed calibration	3.2	0.30
	Vertical Errors (2 Sigma)	
	Real-time (m)	CPAR (m)
Takeoffs	1.8	0.02
Landings	1.4	0.02
Climbs	2.0	0.39
Airspeed calibration	7.6	0.24

Table 2
DGPS Accuracy for Typical Flight Test Manoeuvres

The real-time errors shown in Table 2 were computed for specific (short duration) events such as takeoff and landing, and are therefore smaller than the NSE's shown in Table 1, which were computed for the entire series of approaches. It is also obvious from Table 2 that there is a large difference between the real-time errors and CPAR errors, where the real-time errors are in the order of meters, and the CPAR errors are in the order of centimeters. If accuracy was the only issue, the CPAR solution could be used for all flight test work, since it was generally within the desired one meter accuracy requirement, at least for relative measurements (2 sigma). However, the CPAR solution has the following significant disadvantages:

a. It requires a considerable amount of time for post-flight processing;
b. It cannot be used in flight to determine real-time performance parameters as a guide to progressing to the next test point; and
c. It cannot be used for aircraft guidance.

The real-time solution, on the other hand, is immediately available in flight for the purposes mentioned above, but unfortunately includes errors larger than one meter.

Table 2 also shows the effect of an increasing baseline, or distance between the aircraft and the ground station, on the position and height errors for a single frequency DGPS. With the ground station set up at the airfield, the errors associated with takeoffs and landings are relatively small, while the errors for the climbs, with baselines out to about 15 nautical miles, are larger. The airspeed calibrations, flown at altitudes up to 35,000 feet at distances out to 100 nautical miles, have significantly larger DGPS errors, both real-time and CPAR.

5.2 DGPS Flight Test Application

As noted earlier, the DGPS latitude, longitude and height information was translated into an x,y,z coordinate system which was referenced horizontally to the GPI point, and vertically to the runway threshold. The "x" axis gave the distance along the runway length, while the "y" axis gave the deviation (left or right) from the runway centreline. The "z" axis gave the height of the aircraft main wheels above the runway surface as a function of the aircraft pitch angle and fixed GPS antenna position. The real-time x,y,z values, along with the DGPS-derived groundspeed, were displayed on one of the data pages of the cockpit CDU. When lining up for takeoff, the pilot could monitor the accuracy of these parameters in comparison with his position on the runway, thus ensuring the proper functioning of the differential link prior to takeoff.

The recording of aircraft distance along the runway led to a simple data reduction scheme for airfield performance manoeuvres such as takeoffs and landings. The takeoff distance to a 35 foot screen height was determined simply by establishing the aircraft x-axis position at a DGPS height of 35 feet (11 meters) above the lift-off point, and then subtracting this value from the x-axis position recorded at the beginning of the takeoff roll. The landing distance from 50 feet (15 meters) above the runway to a complete stop was determined in the same manner. Real-time DGPS position errors of about 1.5 meters in the horizontal plane were slightly higher than the desired measurement accuracy. However, because of the dependence of takeoff and landing distances on height above the runway, the real-time DGPS height errors of about 2.0 meters influenced their measurement accuracy to an unacceptable extent.

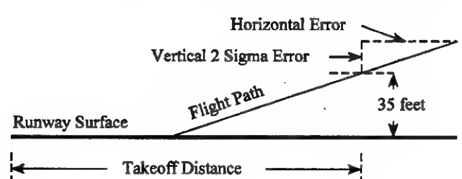


Figure 5
Effect of Vertical Errors on Measurement Accuracy

Figure 5 shows how the measurement of takeoff distance is dependent on climb gradient and DGPS height accuracy (2 sigma for a 95% confidence level). For a low climb gradient of about 5%, typical of single engine performance, a 2.0 meter error in height would result in a 40.0 meter uncertainty in the measurement of takeoff distance, representing about 4.0% of a typical Falcon 20 takeoff distance of 1000 meters. The measurement of landing

distance from a height of 50 feet (15 meters) would be similarly affected, with a 3 degree glidepath angle being roughly equivalent to a 5% gradient. On the other hand, flight test manoeuvres performed only in the horizontal plane, such as rejected takeoffs and V_{mcg} ground runs, were not affected by errors in height, and could be measured (real-time) to within about 1.5 meters. This figure represents a very small percentage of a rejected takeoff roll, but a much higher percentage of the deviation permitted left or right of the runway centreline during V_{mcg} testing.

To simulate autopilot coupled landing performance, the DGPS-derived aircraft touchdown positions were recorded in comparison with videotaped images of the actual aircraft touchdown points on the runway. Unfortunately, these comparisons were inconclusive due to the lack of a functional weight-on-wheels switch during the actual tests. In addition, with a DGPS sample rate of only 5 Hz applied at landing speeds of about 200 feet/sec (61 meters/sec), an ambiguity of about 40 feet (12 meters) existed in the aircraft touchdown point. This was considerably larger than the absolute (*mean* + 2 sigma) horizontal error of 2.1 meters for landings, even with signal latency and transport lag included. For future tests, the sample rate would have to be high enough for the desired level of accuracy, or an interpolation routine would have to be implemented.

The existing Falcon 20 guidance with DGPS proved useful for test points such as simulated autopilot malfunctions on a precision approach glidepath and community noise test profiles. Since vertical deviations from the glidepath were already being computed and recorded for the purpose of providing guidance, they could also be used to determine the extent of autopilot induced pitchover and recovery time. Lateral guidance was essential to accurately fly community noise profiles to selected noise recording sites. For these tests, the DGPS reference point was changed from the GPI point to the end of the active runway, and the lateral steering sensitivity was increased from a precision approach setting of ±350 feet (107 meters) to ±250 feet (76 meters) full scale deflection. A track down the runway centreline could be flown at low altitude, or intercepted from takeoff, to a simulated noise recording site at the end of the runway. The lateral steering accuracy achieved was about 4.5 meters (one sigma), slightly better than the FTE of 5.5 meters shown in Table 1, due to the increased sensitivity. Increasing the steering sensitivity beyond ±250 feet (76 meters) full scale deflection resulted in undesirable lateral tracking oscillations left and right of track.

Airspeed calibration test points were flown in "windbox" patterns to demonstrate that DGPS-derived groundspeed and track could be used to determine the true airspeed of the aircraft by eliminating the wind vector determined from reciprocal flight tracks. This process has evolved to a more comprehensive calibration of aircraft position error and airflow angles using DGPS measurement techniques, and is described in Reference 3.

The NovAtel 951R DGPS system described in sub-section 3.2 was demonstrated to be a viable measurement tool for the flight test manoeuvres flown with the Falcon 20, but it's real-time position and height accuracies did not meet the desired values. This resulted in unacceptable errors in the measurement of certain performance parameters, particularly takeoff and landing distances, where shallow climb or descent gradients translated small height errors into large horizontal errors. The next section will describe the accuracies obtained with an upgraded DGPS system, the NovAtel RT-20, and its application to the measurement of Falcon 20 landing performance on contaminated runways.

6.0 LANDING PERFORMANCE TESTS

It was clear that the real-time accuracy of the Falcon 20 DGPS had to be improved prior to using it as a primary flight test measurement tool for aircraft landing performance on winter contaminated runways. Two NovAtel RT-20 GPS receivers were obtained and installed as replacements for the 951R receivers in both the Falcon 20 aircraft and the DGPS ground station. Like the 951R, the RT-20 was a single frequency receiver card installed in a PC-compatible computer. However, the RT-20 incorporated double differencing techniques, based on carrier phase measurements and a floating ambiguity program, to provide real-time accuracies at the 20 centimeter level within a few minutes after system power up. It had a significant performance advantage over the 951R through the real-time incorporation of carrier phase ambiguity resolution. Other than the type of GPS receiver used, the DGPS system setup for the landing performance tests was identical to that shown in Figure 2.

6.1 Upgraded DGPS Accuracies

The validation of the RT-20 real-time position and height accuracies was done in comparison with the Ashtech TSPI during the first nine flights of the actual performance testing done at the airport in North Bay, Ontario. The flights included typical airfield performance manoeuvres within a 15 nautical mile baseline from the ground station, including maximum performance takeoffs, landings, and accelerate/stops. As with the previous DGPS accuracy tests, both real-time and post-flight CPAR solutions were obtained.

The post-flight processed CPAR solution for the RT-20 was within 3 centimeters (one sigma) of the Ashtech TSPI solution, with survey biases removed. This provided strong support to the qualification of the NovAtel RT-20 as a TSPI, in its own right, for short baseline flights. The differences between the RT-20 real-time solutions and the Ashtech TSPI (2 sigma values) are shown in Table 3 for each of the nine flights.

	Two Sigma Errors (meters)	
Flight No.	Horizontal	Vertical
01	0.48	0.14
02	**0.70**	0.22
03	0.16	0.18
04	0.30	0.12
05	0.48	0.14
06	**1.06**	**0.40**
07	0.54	0.20
08	0.26	0.32
09	**0.74**	0.30

Table 3
RT-20 Real-time DGPS Accuracy versus Ashtech TSPI

The errors shown for each flight in Table 3 are computed for the entire time of operation of the RT-20, from power-up to shutdown, including the period of initial convergence of the latitude, longitude, and height parameters during static operation on the ramp. Relatively high initial errors in longitude occurred prior to convergence, especially on flights 02, 06 and 09, and these affected the overall horizontal errors for these flights (shown in bold print). Disregarding the effects of initial convergence, the airborne horizontal errors were generally less than 0.5 meters (2 sigma).

Since the horizontal error is equal to the root-sum-square of the errors in latitude and longitude, the individual one sigma errors of latitude and longitude were less than 20 centimeters, meeting the manufacturer's performance specification.

The vertical errors shown in Table 3 were generally less than 0.3 meters (2 sigma) except for flight 06 (shown in bold print), which was affected by a relatively large initial convergence error in height. The effect of this vertical error on the measurement of takeoff or landing distance, assuming a shallow climb or descent gradient of 5%, would be an uncertainty of about 6.0 meters in the horizontal plane. This is less than 1% of a typical Falcon 20 takeoff or landing distance, and represents a significant improvement over the results described in sub-section 5.2.

6.2 Test Objectives and Procedures

The primary objectives of the landing performance tests were:

a. to determine the Falcon 20 coefficient of braking and contaminant drag for various contaminated runway surfaces; and
b. to determine the Falcon 20 landing distances for various contaminated runway surfaces, and use these data to validate or refine the existing James Brake Index (JBI) tables in the Transport Canada Aeronautical Information Publication (AIP, Reference 4).

The JBI is a runway friction index between 0.0 and 0.8, used in Canada to give the pilot of an incoming aircraft the anticipated braking performance on the active runway. A JBI of 0.8 is representative of maximum braking capability on a bare and dry runway surface, while a JBI of 0.0 is representative of zero braking. A surface covered with wet ice may have a JBI of 0.1; a surface covered with loose snow may have a JBI of 0.3; and a rain soaked surface may have a JBI of 0.5. The value of the JBI is determined by an electronic recording decelerometer (ERD) mounted on a ground test vehicle which does several braking runs at intervals along the runway surface.

The North Bay airport, shown in Figure 6, was used as the test site, with Runway 31 designated as the primary test surface. A 1500 foot (450 meters) test section was set up on Runway 31, starting at 1000 feet (300 meters) from the runway threshold and ending just short of the intersection between Runways 13-31 and 08-26. The test section could be purposely covered with various types of contaminants (snow, slush, ice) by airport vehicles for unrestricted testing by the Falcon 20 and the various ground friction vehicles. The test section was covered to about 80 feet (25 meters) in width, centred on the runway centreline, leaving a bare and dry surface on each edge of the runway to allow the pilot to regain control of the aircraft in the event of a lateral departure from the test surface. Runway 13-31 remained closed to normal airport traffic throughout the test period.

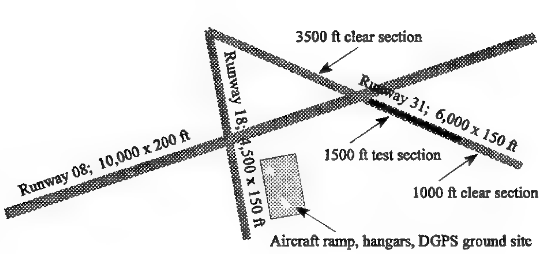


Figure 6
North Bay Airport Runway Layout

The location of the test section on Runway 31 was planned to accommodate both ground runs and landings. Starting at the threshold of Runway 31, the aircraft could accelerate to about 80 knots prior to entering the test section for a braking run. Approaches for landings were made on a 3 degree glidepath, using DGPS guidance, to a GPI point 400 feet (120 meters) from the threshold of Runway 31. This allowed a distance of about 600 feet (180 meters) for the nose to be lowered and the airbrakes to be extended prior to entering the test section for a high speed run. The last 3500 feet (1070 meters) of Runway 31 was kept bare and dry to permit maximum performance braking following a potentially high speed exit from the test section.

Prior to each flight, the test section was prepared by the airport maintenance vehicles to a desired surface condition, and a qualitative description of the surface was recorded. The ground test vehicle then conducted runs to determine the JBI, after which the aircraft conducted a flight which included several landings and accelerate/stop manoeuvres with full anti-skid braking applied throughout the test section. Following the aircraft flight tests, the ground test vehicle conducted a second series of runs to determine a JBI which could be compared, and averaged if appropriate, with the initial value.

The total landing distance (LD) was computed as the sum of the following three distances, shown in Figure 7:

a. Air distance (D1) = horizontal distance from a height of 50 ft above the touchdown zone elevation (GPI point) to the aircraft touchdown point (weight on wheels);
b. Delay distance (D2) = distance from touchdown to airbrake extension and application of full braking; and
c. Braking distance (D3) = distance from the application of full braking to a complete stop.

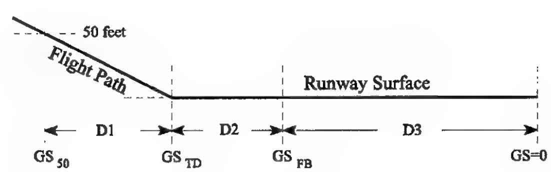


Figure 7
Landing Distance Definition

DGPS-derived aircraft groundspeed (GS) was determined at the start of each landing segment as shown in Figure 7. The groundspeed at 50 feet (15 meters), labelled GS_{50}, was assumed to be the same as the approach groundspeed for the purpose of comparison with the Aircraft Flight Manual (AFM) landing distance. The groundspeed at touchdown (GS_{TD}) was recorded at the engagement of the aircraft weight-on-wheels switch, and the groundspeed at full braking (GS_{FB}) was recorded at the application of full braking as determined by data from the brake pressure transducers.

DGPS-derived aircraft positions were used to determine actual air distances and delay distances. In a manner similar to that described in sub-section 5.2, the air distances, D1, were determined by finding the aircraft x-axis position at a DGPS height of 50 feet (15 meters) above touchdown, and subtracting this value from the x-axis position recorded at the touchdown point. Delay distances, D2, were calculated in the horizontal plane between the touchdown point and the application of full braking. Braking distances, D3, could not be measured directly with DGPS positioning, because the Falcon 20 could not generally be stopped completely within the 1500 foot (450 meter) test section, especially

with the lower JBI's, from its nominal brake application speed of 100-110 knots. Instead, the braking distance for a particular surface condition had to be computed as the sum of two distances resulting from two separate test runs within the test section. A performance landing produced a high speed full braking segment (about 110 knots down to 65-75 knots), and an accelerate/stop run produced a lower speed full braking segment on the same surface (75 knots down to 20-30 knots). Braking distance was interpolated from acceleration data for any gaps between the speed bands, as well as for groundspeeds below 20-30 knots, where full braking was not accomplished.

The ensuing paragraphs will discuss and compare several different types of "total landing distance" (LD). These are defined as follows:

a. AFM LD: The landing distance taken from the AFM as a function of gross weight, true airspeed, and wind. It is based on very aggressive deceleration techniques on a bare and dry runway surface.
b. Actual LD: The actual landing distance of the Falcon 20 on the various contaminated surfaces as determined from DGPS-derived aircraft positions described above.
c. Predicted LD: The landing distance of the Falcon 20 computed as a function of approach groundspeed (GS_{50}) and JBI, developed in sub-section 6.3.
d. Factored LD: The predicted LD increased by a safety factor which accounts for variations in pilot technique, braking performance, or runway condition, developed in sub-section 6.4.

6.3 Predicted Landing Distance

The DGPS-derived time, speed and distance data recorded during a total of 25 approaches and landings were averaged and used to establish equations for air distance, D1, and delay distance, D2. All approaches were flown using DGPS guidance to a 3 degree glidepath, providing a consistent flight path at least to a height of 200 feet (61 meters), where the pilots took over visually for landing. Even though the pilots attempted to land firmly and lower the nose quickly on all landings, distances D1 and D2 varied considerably with pilot technique. The standard deviations associated with these times and distances were used to determine the factored LD (sub-section 6.4) to a 95% (2 sigma) confidence level. The equations developed for D1 and D2, based on flight test data, are:

$$D1 = 1.55 \times (GS_{50} - 80)^{1.35} + 975 \qquad \textbf{(2)}$$

$$D2 = 4.946 \times (GS_{50} - 9.65) \qquad \textbf{(3)}$$

where distances D1 and D2 are expressed in feet, and approach groundspeed, GS_{50}, is expressed in knots.

For each braking run, the DGPS-derived groundspeed was smoothed and differentiated with respect to time. This DGPS-derived deceleration, dGS/dt, compared very well with the aircraft x-axis accelerometer data, and was easier to use because it did not require a correction to the local horizontal using aircraft pitch angle, as did the x-axis accelerometer data. The parameter dGS/dt was plotted against groundspeed, GS, during each braking run, and found to approximate a linear relationship. Continuing the process for different runway surface conditions, each with a specific JBI value, a three way linear relationship was established among the parameters dGS/dt, GS and JBI, of the form:

$$dGS/dt = (k_1 + k_2 \times JBI) + GS \times (k_3 + k_4 \times JBI) \qquad \textbf{(4)}$$

where k_i are non-dimensional constants. Figure 8 is a graphical representation of this relationship, based on linear approximations, and shows the Falcon full braking deceleration in "g" units plotted against groundspeed in knots for JBI values between 0.0 and 0.8.

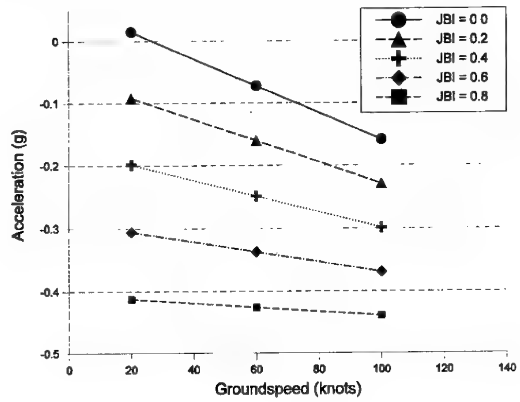


Figure 8
Full Braking Deceleration versus GS and JBI

An equation for braking distance, D3, was developed as a function of approach groundspeed and average deceleration, dGS/dt_{AV}, during the braking run. The average deceleration was computed at a point midway through the braking run as a function of approach groundspeed and JBI, as expressed in Equation (4) and shown in Figure 8. This equation is:

$$D3 = \frac{-((GS_{50} - 13.15) \times 1.69)^2}{64.35 \times dGS/dt_{AV}} \qquad \textbf{(5)}$$

$$\textit{where } dGS/dt_{AV} = (k_1 + k_2 \times JBI) + \frac{(GS_{50} - 13.15)}{2} \times (k_3 + k_4 \times JBI)$$

Using Equations (2), (3) and (5) for the three components of the total landing distance, the predicted LD can now be determined as a function of GS_{50} and JBI from the equation:

$$\textit{Predicted LD} = D1 + D2 + D3 \qquad \textbf{(6)}$$

To a large extent, Equation (6) is based on an accurate modelling of aircraft deceleration under full anti-skid braking versus both groundspeed and JBI number. In fact, the standard deviation of the linear curve fit was 0.022 "g" units, which represents about 10% of the average deceleration at mid values of JBI. This number will be applied to the factored LD developed in sub-section 6.4.

A comparison of actual LD's, determined from DGPS-derived aircraft position data, and predicted LD, determined from Equation (6), is shown in Figure 9. The data points in the figure are reasonably close to a line of equality between the actual LD and the predicted LD, demonstrating the validity of Equation (6). The fact that some points are above the line of equality (actual LD greater than predicted) simply indicates that the actual aircraft decelerations during the braking runs (for these points) were above the modelled curve fit (less deceleration than modelled), resulting in a longer actual LD. The concept of a factored LD exists because it is undesirable to use an equation for predicted LD which underestimates the actual landing distance.

To be most useful to the pilot, and independent of aircraft type, predicted LD's should be presented in comparison with the AFM LD's determined prior to each landing, and for the reported value of the JBI for the runway in use.

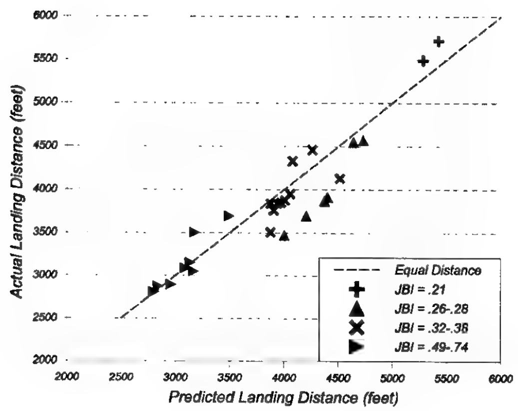


Figure 9
Falcon 20 Actual LD versus Predicted LD

The Falcon 20 AFM LD was approximated as a function of approach groundspeed, GS_{50}, for a full range of landing gross weights, and then compared to the predicted LD from Equation (6) using GS_{50} as a common link. The result of this comparison is a plot of predicted LD versus JBI for selected values of the AFM LD, shown in Figure 10. Since the AFM LD is determined for a bare and dry surface (JBI = 0.8), the predicted LD can be compared directly to the AFM LD at this value of the JBI. Figure 10 shows the predicted LD to be about 400 feet (120 meters) higher than the AFM LD at JBI = 0.8, primarily due to the increased air distances, D1, and delay distances, D2, obtained during testing as compared to AFM certification data. The predicted LD increases markedly with decreasing JBI, reaching a value about double the AFM LD at a JBI of 0.2, equivalent to a runway surface covered with hard packed snow or rough ice.

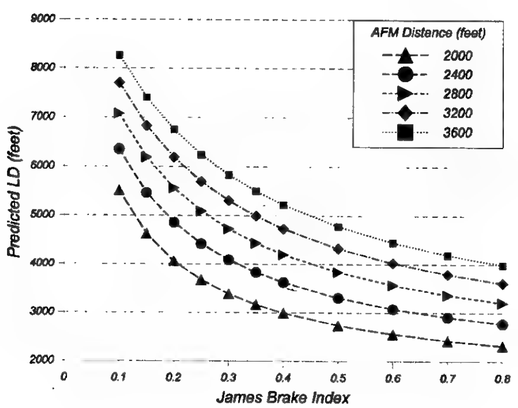


Figure 10
Falcon 20 Predicted LD versus JBI and AFM LD

6.4 Factored Landing Distance

By current regulation, the factored (or required) landing distance is equal to the AFM LD divided by 0.6, applicable only to bare and dry runway surfaces. To apply a safety factor to all runway surface conditions, with a 95% level of confidence that the aircraft could come to a complete stop within the stated distance, equations were developed for the factored air distance, $D1_F$, delay distance, $D2_F$, and braking distance, $D3_F$. The factored LD was computed from the equation:

$$Factored\ LD = D1_F + D2_F + D3_F \qquad (7)$$

The data from 25 approaches and landings were used to determine a two sigma time delay which was applied to D1 and D2 to obtain $D1_F$ and $D2_F$. This amounted to an additional 1.7 seconds for $D1_F$ and 1.9 seconds for $D2_F$. The factored braking distance, $D3_F$, was obtained by decreasing the modelled deceleration by a one sigma value of 0.022 "g" units, and using only 75% of the reported value of the JBI to account for changing weather conditions or non-uniform runway surface conditions. The factored LD's thus obtained were compared to AFM LD's and predicted LD's for different values of JBI. Figure 11 shows the specific case where AFM LD = 2800 feet (850 meters). The landing distances from the existing JBI tables in the Transport Canada AIP compare reasonably well with the predicted LD's, but the factored LD's are much higher. The factored LD's are approximately equal to AFM LD/0.6 at a JBI value of 0.8, and progressively less than predicted LD/0.6 as the JBI values decrease.

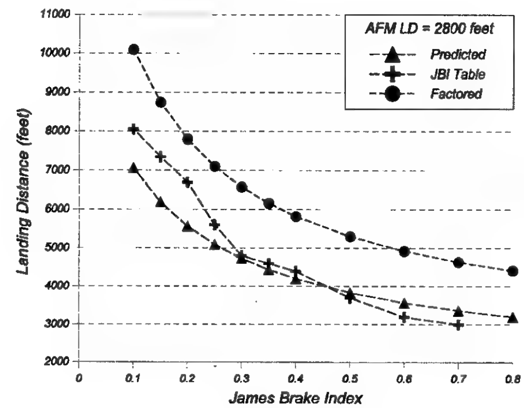


Figure 11
Comparison of LD's for AFM LD = 2800 feet

7.0 CONCLUSIONS

DGPS systems were successfully used to provide Falcon 20 aircraft guidance on precision approaches, and to measure flight test performance parameters. An upgraded DGPS, the NovAtel RT-20, provided real-time position and height accuracies of less than 20 centimeters (one sigma), and was used effectively to determine aircraft landing performance on winter contaminated runways.

8.0 REFERENCES

1. Youngdahl, G.E., "Transport Canada GPS Ashtech Z-12 Test Results", ION Conference, Anaheim, California, January 1995.
2. Kelly, R.J. and Davis, J.M., "Required Navigation Performance (RNP) for Precision Approach and Landing with GNSS Application", Journal of The Institute of Navigation, Vol. 41, No. 1, Spring 1994.
3. Hui, K., Srinivasan, R. and Baillie, S.W., "Simultaneous Calibration of Aircraft Position Error and Airflow Angles using Differential GPS", CASI Conference, Ottawa, Canada, April 1996.
4. "Transport Canada Aviation Aeronautical Information Publication", TP2300E, Ottawa, Canada, July 1996.

Precision Navigation and Synthetic Vision for Poor Visibility Guidance

G. Sachs[1], K. Dobler[2]
Technische Universität München
LSt.f. Flugmechanik u.Flugregelung
Arcisstrasse, 21, 80290 München, Germany

G. Schänzer[3], M. Dieroff[4]
Technische Universität Braunschweig

Abstract

Computer generated synthetic vision is considered as a means for providing guidance in poor visibility conditions. The synthetic vision comprises as basic elements a 3-dimensional image of the outside world and integrated guidance information like a tunnel display. A precision navigation system is applied which couples differential satellite and inertial sensor data to achieve the required high performance. A flight test program was conceived to cover a wide range of synthetic vision guidance applications (precision approach and landing, low level flight in narrow river valley, curved/steep/short approaches and terrain following in moutainous areas). Four test series at different areas were conducted. The results of the flight test program show that the synthetic vision enables the pilot to precisely control the aircraft. He successfully performed the flight tasks.

Introduction

Good visibility or adequate visual aids are essential for a pilot when controlling an aircraft in flight at low height. This particularly holds for flight operations close to the ground such as approach and landing or low level flight. Poor visibility conditions yield great restrictions for aircraft operations. For coping with these problems, complex technical systems are required like the ILS instrument landing system which needs installations both on board of the aircraft and on the ground.

Currently, new concepts known as „Synthetic Vision" or „Enhanced Vision" are considered for providing the pilot with artificial visual cues on board of the aircraft and for supporting him in case of poor outside visibility (Refs. 1-3). Some of these concepts employ sensor based information from radar or optical sensors (Refs. 2, 3).

The approach presented in this paper is based on synthetic vision generated by a computer and on precision navigation provided by satellite navigation. (Refs. 1, 4, 5). The synthetic vision computer generates a 3-dimensional image of the outside world using a stored data base containing all relevant information of the terrain and its objects. A guidance symbology featuring innovative elements forms an integral part of the synthetic vision imagery. A precision navigation system is required for providing the synthetic vision computer with accurate position and attitude information. The high navigation performance is achieved with an integrated DGPS/INS system which couples differential satellite and inertial sensor data.

The flight tests reported in this paper were carried out in a close cooperation of the Institute of Flight Mechanics and Flight Control of the Technische Universität München and the Institute of Flight Guidance and Control of the Technische Universität Braunschweig. Further partners were the ESG Elektroniksystem- und Logistik-GmbH, München, and the Institute of Applied Geodesy, Potsdam.

Synthetic Vision Concept

The approach for an advanced guidance system as presented in this paper consists of computer generated synthetic vision in combination with an integrated DGPS/INS system for precision navigation (Fig. 1). The system comprises two basic elements for generating an image and displaying it to the pilot:

[1] Prof. Dr.-Ing. Gottfried Sachs, Director, Institute of Flight Mechanics and Flight Control.

[2] Dipl.-Ing. Klaus Dobler, Research Assistant, Institute of Flight Mechanics and Flight Control.

[3] Prof. Dr.-Ing. Gunther Schänzer, Director, Institute of Flight Guidance and Control.

[4] Dipl.-Ing. Manfred Dieroff, Research Assistant and Engineering Pilot, Institute of Flight Guidance and Control.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

- A realistic 3-dimensional image of the outside world is provided by a graphics computer. The computer makes use of a stored database containing all relevant information of the terrain and its elevation as well as of buildings, obstacles etc. In addition, flight guidance information is presented as an integral part of the synthetic vision imagery.

  A special real-time software was developed which is capable of generating the described synthetic vision imagery in an adequate update rate (30 images per sec).

- A precision navigation system is used for providing accurate position and attitude data which are transferred to the synthetic vision computer. The required navigation performance is achieved with an integrated navigation system which couples differential global positioning (DGPS) and inertial sensor data and additionally uses computer and filter algorithms. The position accuracy attained with this system is in the submeter range.

A comprehensive data base for generating a 3-dimensional image of the outside world was produced, and use was made of various data sources (digitized mapping material, photographs etc.). The data is basically organized in two groups:
- terrain elevation data
- terrain feature data

For describing the elevation of the terrain, a grid is used the elements of which have a size of 3"×3" (or 1"×1"), Fig. 2. These values correspond to a width of $90\ m \times 60\ m$ (or $30\ m \times 20\ m$) at the geographical latitude of the flight test areas. The computer memory required for storing the elevation data for an area like Germany is about 125 MByte (with 3"×3" grid elements).

The feature data concerns the characteristics of the terrain including the objects on the terrain. Three feature types are used (Fig. 3):
- point features (buildings, bridges, power line pylons, etc.)
- linear features (roads, railsways, rivers etc.)
- areal features (cities, forests, waters etc.)

The representation of terrain feature data and their assignment to the elevation grid is illustrated in Fig. 3.

The computer generated 3-dimensional image of the outside world is combined with guidance information which is considered an integral part of synthetic vision. Innovative guidance elements are introduced for improving the information of the pilot. As an example, a tunnel image was displayed for indicating the nominal trajectory which the pilot should follow. The tunnel display included additional information of the actual trajectory and flight conditions. Fig. 4 shows the integration of the tunnel and the outside world imagery.

Precision Navigation and Test Aircraft

For exploiting the possibilities of synthetic vision as an innovative means for full visual information of the pilot, a precision navigation system is required which provides position data with high accuracy. The required high performance can be achieved with a navigation system developed at the Institute of Flight Guidance and Control of the Technische Universität Braunschweig. The system basically couples differential satellite navigation and inertial sensor data and applies computational algorithms for error modelling, yielding an integrated precision DGPS/INS navigation system. The elements of the system which provides position, speed and attitude data are schematically illustrated in Fig. 5. Further details of the configuration of the DGPS/INS navigation system used in the flight test series are shown in Fig. 6.

The navigation system was operated in two modes for transmitting the differential correction data of the DGPS component (Fig. 7):
- Local-Area-DGPS mode using a customised ultra high frequency data link
- Wide-Area-DGPS mode using a transmitter in the low frequency band

The Local-Area-DGPS mode was applied in the approach and landing flight tests. The GPS reference station which was installed close to the runway was equipped with a Novatel GPS-receiver and an ultra-high frequency telemetry with 4800 baud using a raw data format. In the Local-Area-DGPS mode, it was possible to achieve a very high accuracy (better than 0.5 meter, Fig. 8).

The Wide-Area-DGPS mode was used for the low level flight tests in the Altmühl river valley and in the mountainous Schwarzwald area. This is because the Local-Area-DGPS technique using a ultra high frequency data link shows a reduced availability in case of hiding terrain formations. In order to avoid such deficiencies, a low frequency transmitting technique was used for providing the correction signal (Fig. 9). The technique applied in the flight test series was developed by the Institute of Applied Geodesy in Potsdam which has gained experience in this field for several years (Ref. 6). The low frequency data are transmitted in a format provided by the Radio Technical Commission for Maritime Services

(RTCM). The achievable accuracy depends on the baseline length as shown in Fig 8.

The integrated precision navigation system is a main element of the equipment of the test aircraft which is a twin engine Dornier Do 128 (Fig. 10). This vehicle is oprated by the Institute of Flight Guidance and Control of the Technische Universität Braunschweig as a research aircraft. The aircraft features additional sensor and test equipment like an air data measurement system and other test devices.

The precision DGPS/INS navigation system applied in the flight tests is based on experience in satellite navigation for many years. A great variety of flight tests on precise trajectory measurement and control was conducted. The research aircraft was used for performing the first automatic landing with the use of a DGPS/INS navigation system (Ref. 7). It may be also of interest to note that the experience gained in satellite navigation includes the GLONASS system (Ref. 8).

Synthetic Vision Display and Test Equipment

For flight testing the synthetic vision system, a high performance graphics computer (Silicon Graphics Onyx) and some other components for in-flight monitoring and data recording were installed on board of the research aircraft (Fig. 10).

Various display possibilities may be used for presenting the synthetic vision imagery to the pilot (Fig. 11). A head mounted display was chosen due to of installation and certification reasons.

The basic arrangement of the head mounted display is illustrated in Fig. 12. Two models of head mounted displays were applied. The model used in the first flight tests is a customary device which is considered for general applications on the ground (Fig. 13). In later flight tests, an own construction was used which showed some features specifically suited for flight like a pilot helmet to which the optic devices and displays are attached (Fig. 14).

In combination with the head mounted display, a head tracking system was used for measuring the movements of the head of the pilot (Fig. 12). The head tracking system was coupled to the systhetic vision computer. Thus, it was possible to generate an outside world image corresponding to the position and attitude of the head of the pilot.

Flight Test Results

A comprehensive flight test program was conceived for testing for a wide range of guidance applications of synthetic vision. Four flight test series were performed (Fig. 15):

- Precision approach and landing flight tests, Braunschweig airport, October 10-14, 1994
- Low level flight tests in highly curved, narrow river valley, Altmühl river, December 12-16, 1994
- Curved and steep approaches in mountainous area, Lugano airport (Switzerland), July 31 - August 4, 1995
- Curved/short approaches and low level and terrain following flights in mountainous area, Offenburg/Schwarzwald, March 18-22, 1996

Results of the flight test program for various guidance tasks are presented in the following.

The precision approach and landing task is considered in Fig. 16 where altitude histories of some test flights at Braunschweig airport are shown. A flight path similar to an ILS glide slope was used as a reference. The results presented in Fig. 16 show that the pilot accurately controlled the aircraft from the beginning of the approach tajectory until touch down. A special indication of the height above ground contributed to the success of precisely controlling the aircraft in the flight phase immediately before touch down. This indication was provided by a vertical bar displayed in the synthetic vision image. The bar which does not appear until a specified height (30 ft above ground) is reached reduces its lenght according to the aircraft approaching the ground.

Results of low level flight tests in a highly curved, narrow valley environment (Altmühl river) are shown in Figs. 17 and 18. A section of about 20 km is considered out of an overall test track length of 80 km (Fig. 17). This section is particularly demanding for the pilot to control the aircraft, showing a curvature of more than 180 deg with turns in the opposite direction at the begin and the end. The pilot precisely controlled the aircraft and held it on the specified tajectory. Fig. 18 shows that there are rather small deviations which are well within the tolerance limits as provided by the width of the tunnel. (The tunnel layout is shown in Fig. 4, presenting a flight condition of the Altmühl flight tests.)

The flight tests on curved and steep approaches at Lugano airport are illustrated in Fig. 19 which shows three routes indicated as A, B and C. Mountains in the extended centerline of the runway are of particular concern for performing approaches. The test results show that the pilots successfully accomplished the control tasks and accurately followed the specified approach routes. This is illustrated in Fig. 20 which shows results from an approach flight test on route B. This approach route section includes a 180 deg turn which appears as an unwound curve in the presentation of Fig. 20.

Results from the Offenburg/Schwarzwald flight tests are presented in Figs. 21 and 22. Fig 21 shows the final phase of the test track leading out of a narrow river valley (Kinzig river) into a short base and the final approach segment. The river valley flight route and the approach segment are connected with a S-curve because of a mountain in between. The results presented in Fig. 22 which concerns a section of the trajectory including the turn before the final approach segment shows that the flight path stays well within the limits of the guidance tunnel.

Conclusions

The concept of an advanced guidance system comprising computer generated synthetic vision for poor visibility flight is considered. This system generates a 3-dimensional image of the outside world and an integrated guidance symbology featuring innovative elements like a tunnel display. The outside wourld image is based on stored data containing all relevant terrain information. A precision navigation system is coupled to the synthetic vision computer. The required high navigation performance was achieved with an integrated navigation system coupling differential global positioning and inertial sensor data. The differential satellite navigation system was operated in local and wide area modes for transmitting the differential correction data.

A flight test program was conceived for covering a wide range of guidance applications of synthetic vision. Flight tests were performed in four test series at different locations: precision approach and landing in Braunschweig (Germany), low level flights in Altmühl river valley (Germany), curved and steep approaches in mountainous area in Lugano (Switzerland) and curved/short approaches and terrain following in mountainous area in the Scharzwald (Germany). An especially equipped Dornier 128 research aircraft was used in the flight tests. The results show that the pilot successfully performed the control tasks. He was able to precisily control the aircraft with the use of the computer generated vision and to achieve all goals of the flight test program.

References

1 Möller, H., Sachs, G.: Synthetic Vision for Enhancing Poor Visibility Flight Operation. IEEE Aerospace and Electronics Systems Magazine, Vol. 9, pp. 27-33, 1994.

2 Rathmann, U.: Künstliche Sicht. CCG-Kurs LR 4.05, "Moderne Unterstützungssysteme für Piloten", Carl-Cranz-Gesellschaft, Oberpfaffenhofen, 1992.

3 Nordwall, B.D.: HUD with IR System extends Pilot Vision. Aviation Week & Space Technology, pp. 62-63, Febr. 22, 1993.

4 Sachs, G., Möller, H., Dobler, K., Schänzer, G., Dieroff, M.: Satellite Navigation and Synthetic Vision for Precision Approach in Poor Visibility. Proceedings of the International Symposium on Precision Approach and Automatic Landing, pp. 375-382, Deutsche Gesellschaft für Ortung und Navigation, 1995.

5 Sachs, G., Dobler, K.: Synthetic Vision Flight Tests For Low Level Guidance in Poor Visibility. AIAA Paper 96-3744, 1996.

6 Dittrich, J., Kühmstedt, E., Lechner, W. et al: Experiments with Real Time Differential GPS Using a Low Frequency Transmitter in Mainflingen (Germany) – Results and Experiences. EURNAV 94 Land Vehicle Navigation, Dresden, June 14-16, 1994.

7 Vieweg, S., Schänzer, G.: Präzise Flugnavigation durch Integration von Satelliten-Navigationssystemen mit Inertialsensoren. DGLR-Jahrbuch 1992 I, pp. 171-177, 1992.

8 Schänzer, G.: Präzisionsnavigation. Philip Morris Forschungspreis 1993, Philip Morris Stiftung, München, 1993.

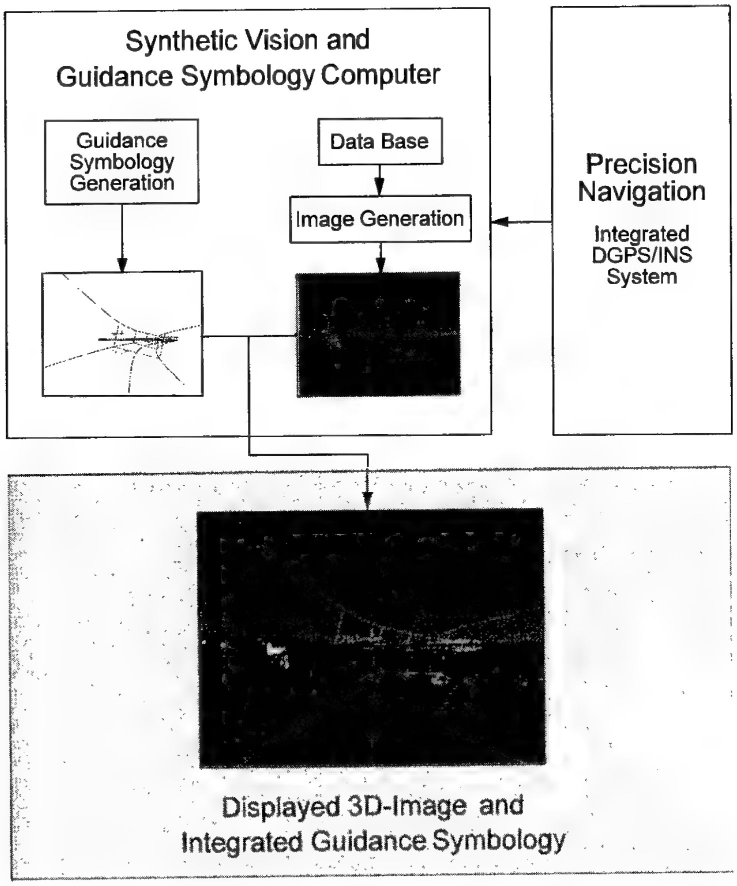


Fig. 1 Concept of computer generated synthetic vision

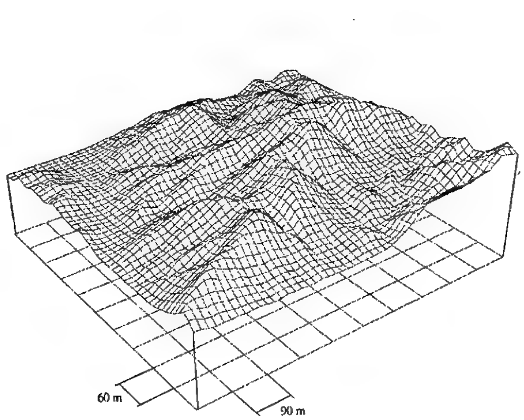


Fig. 2 Representation of terrain elevation

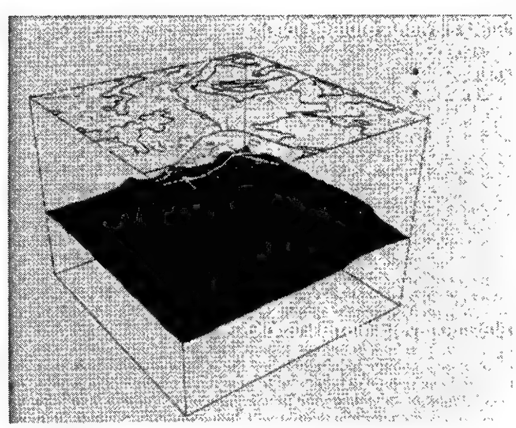


Fig. 3 Representation of terrain features and elevation

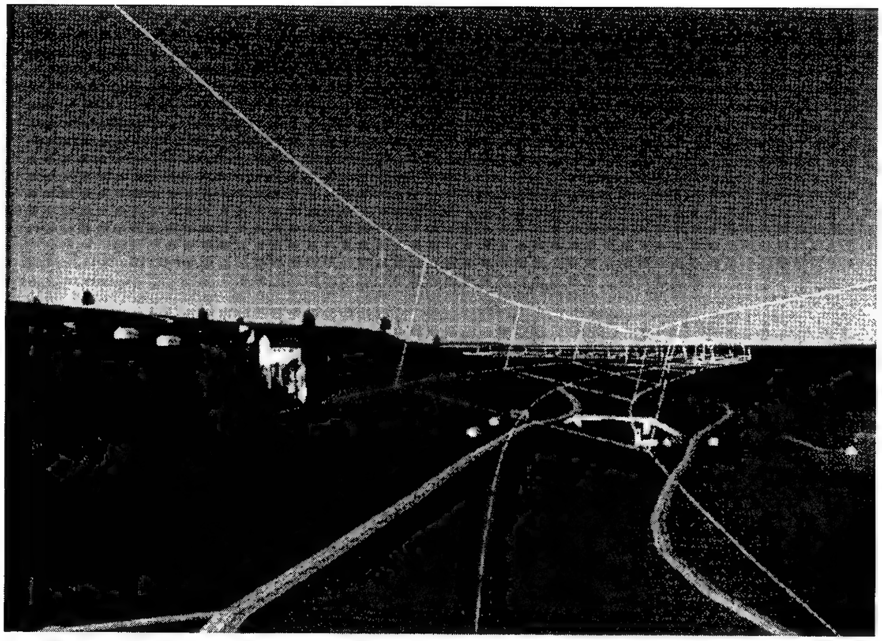


Fig. 4 Synthetic vision imagery with integrated guidance symbology (tunnel), low level flight condition in Altmühl river valley

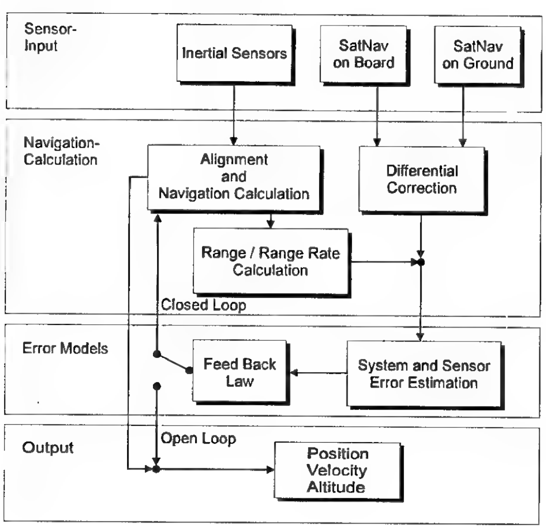


Fig. 5 Schematic of integrated DGPS/INS navigation system used in flight tests

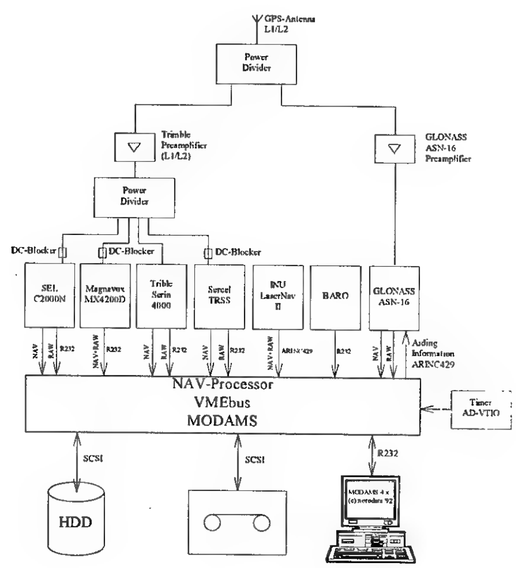


Fig. 6 Configuration of DGPS/INS navigation system used in flight tests

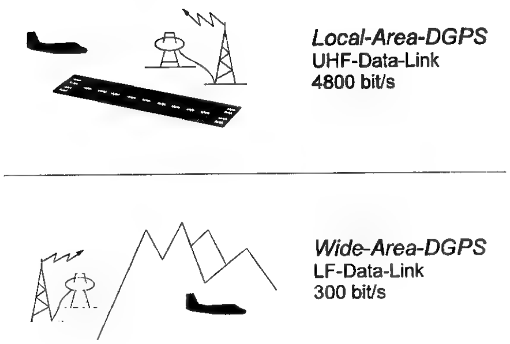


Fig. 7 Local- and Wide-Area-DGPS modes

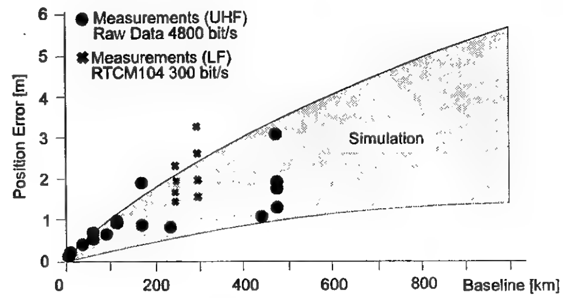


Fig. 8 Position accuracy of the integrated DGPS/INS system (local and wide area operation)

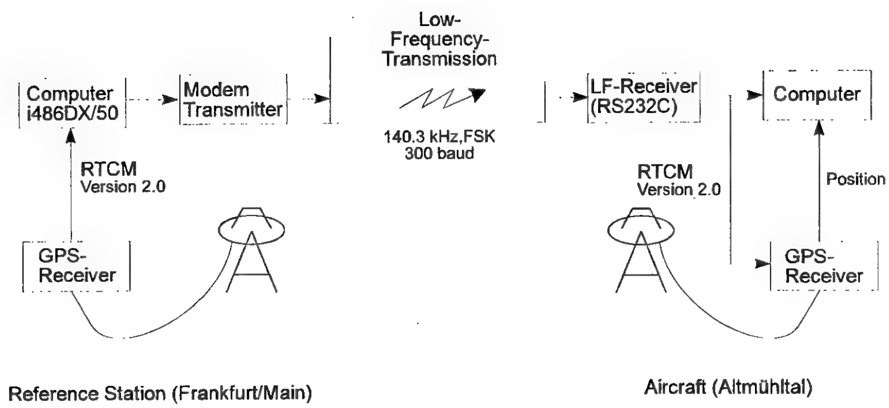


Fig. 9 Wide-Area-DGPS mode

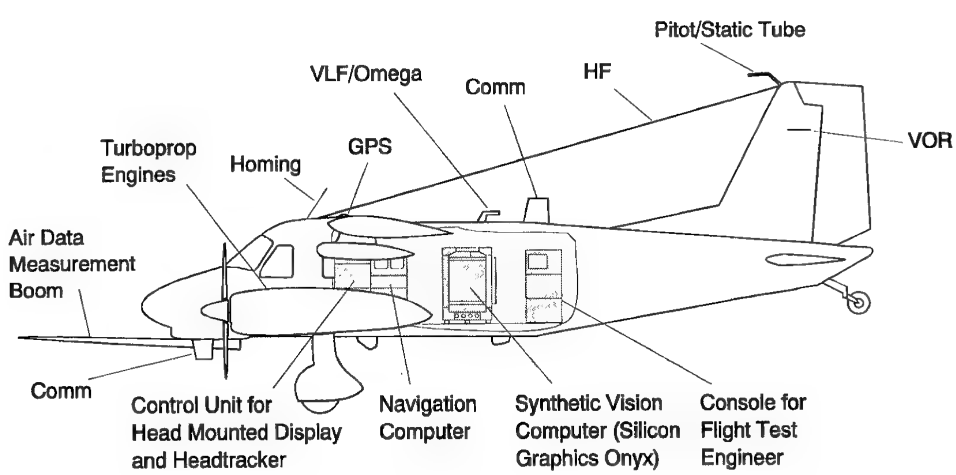


Fig. 10 Test Aircraft

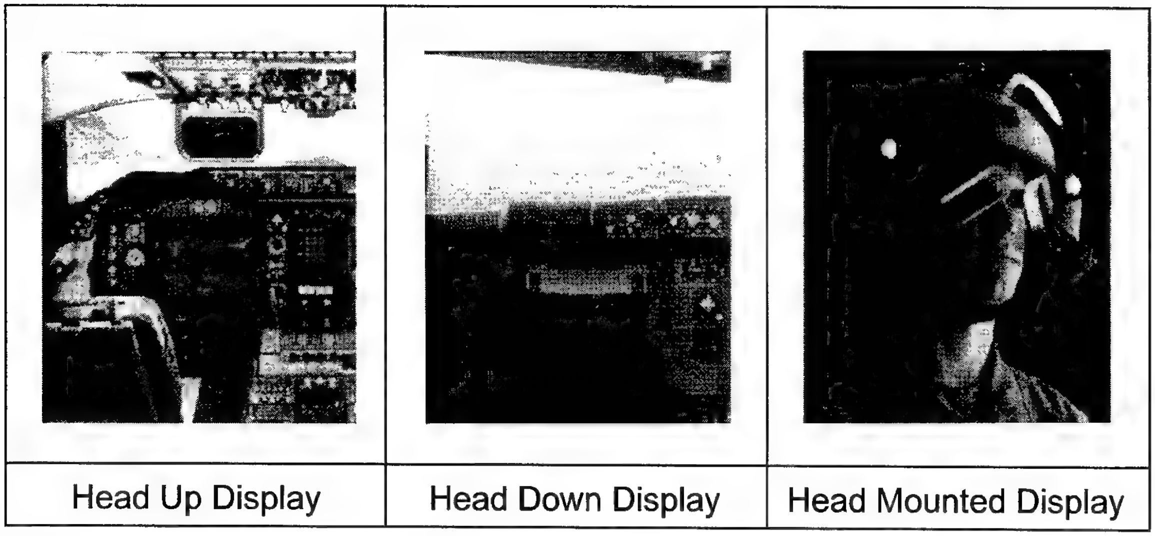


Fig. 11 Display Techniques

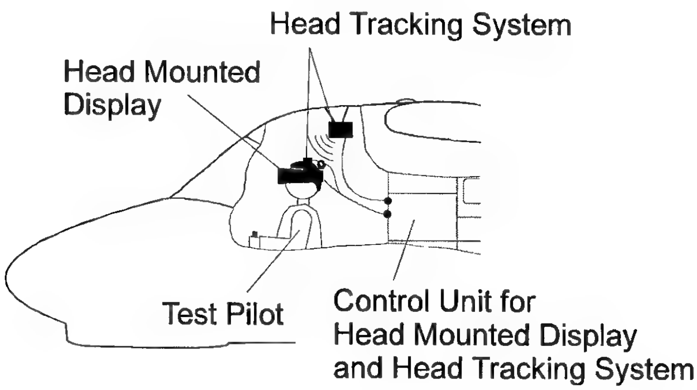


Fig. 12 Head mounted display and head tracking system

Fig. 13 Head mounted display (Datavisor System)

Fig. 14 Head mounted display

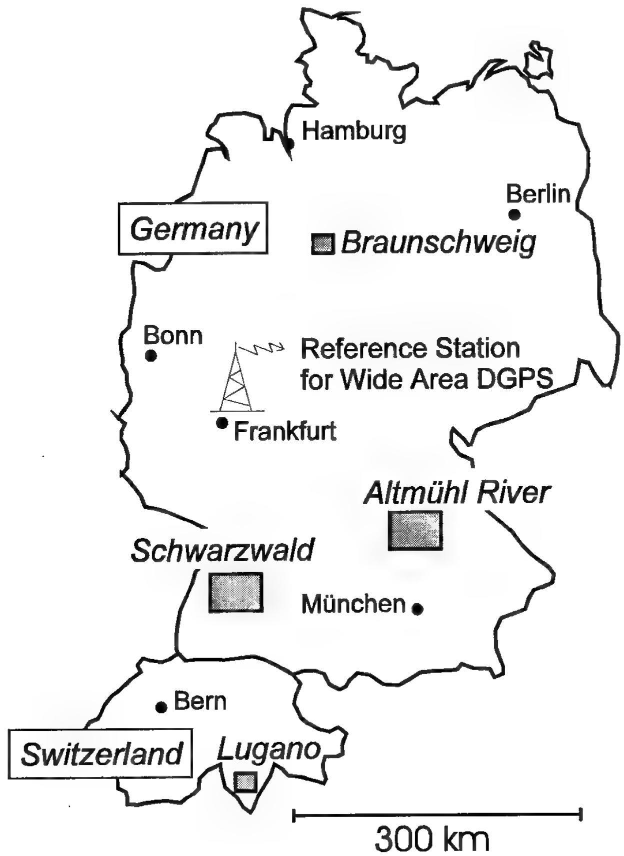


Fig. 15 Flight test areas

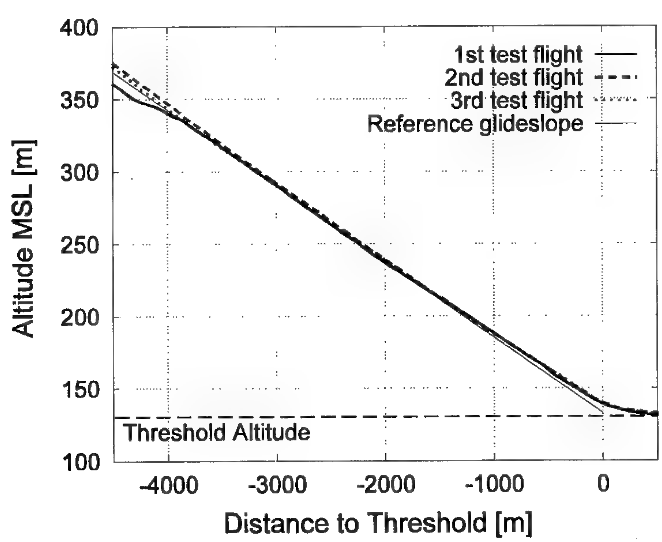


Fig. 16 Results of precision approach and landing flight tests with synthetic vision at Braunschweig airport

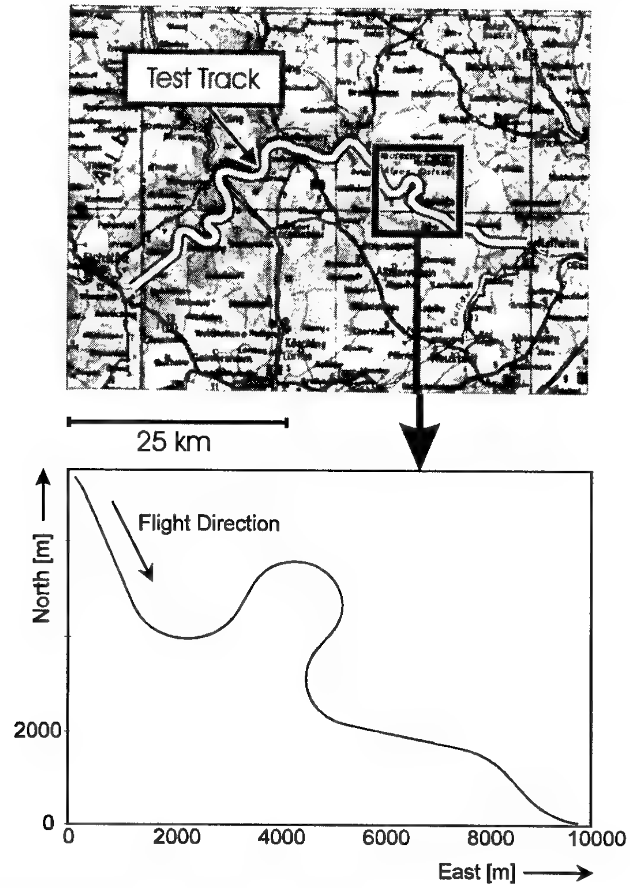


Fig. 17 Low level flight test track in Altmühl river valley

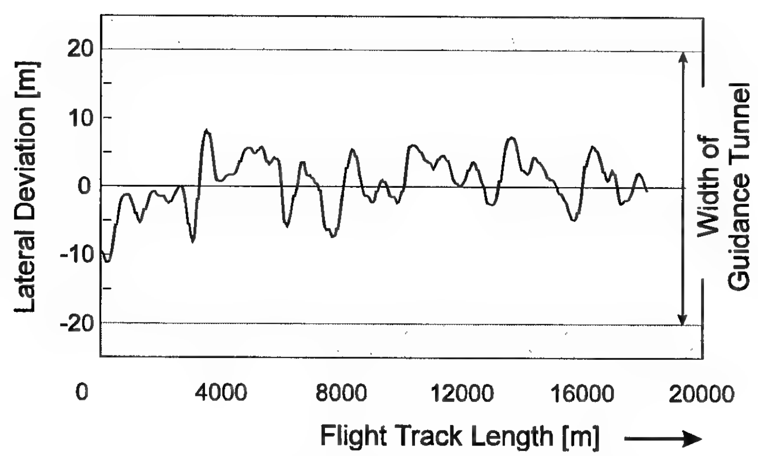


Fig. 18 Results of synthetic vision flight tests in Altmühl river valley (lateral deviations from trajectory section shown in Fig. 17)

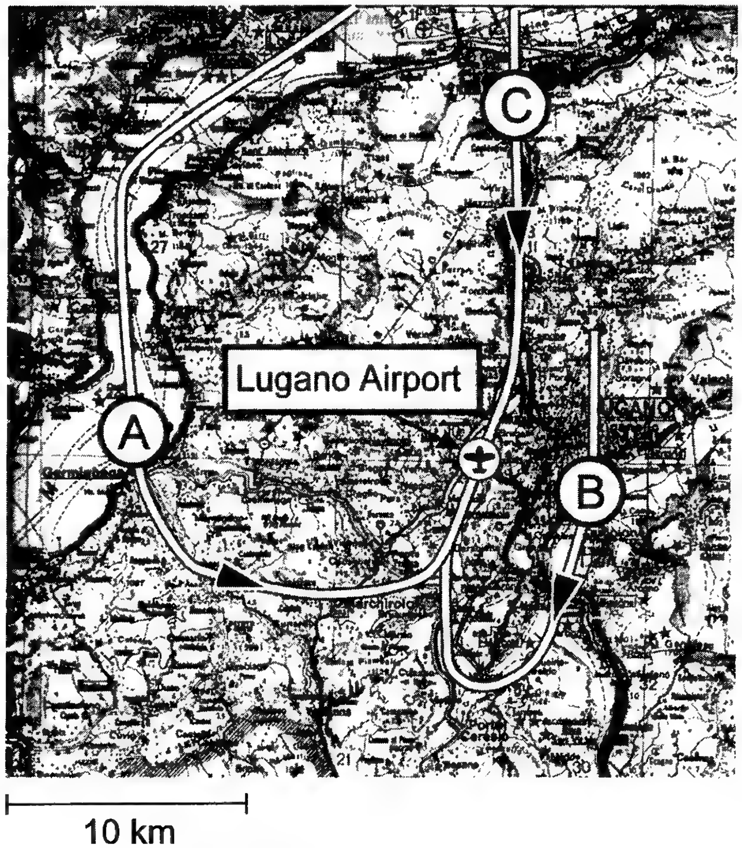


Fig. 19 Flight test routes for curved and steep approaches at Lugano airport

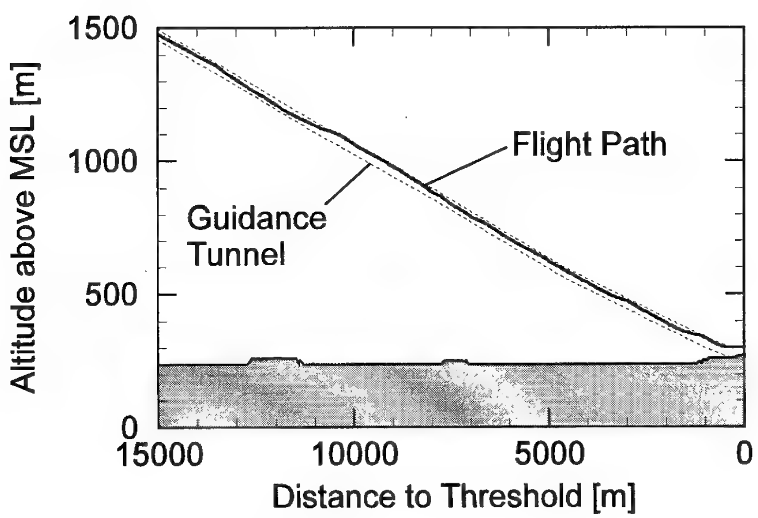


Fig. 20 Flight test results (route B in Fig. 19)

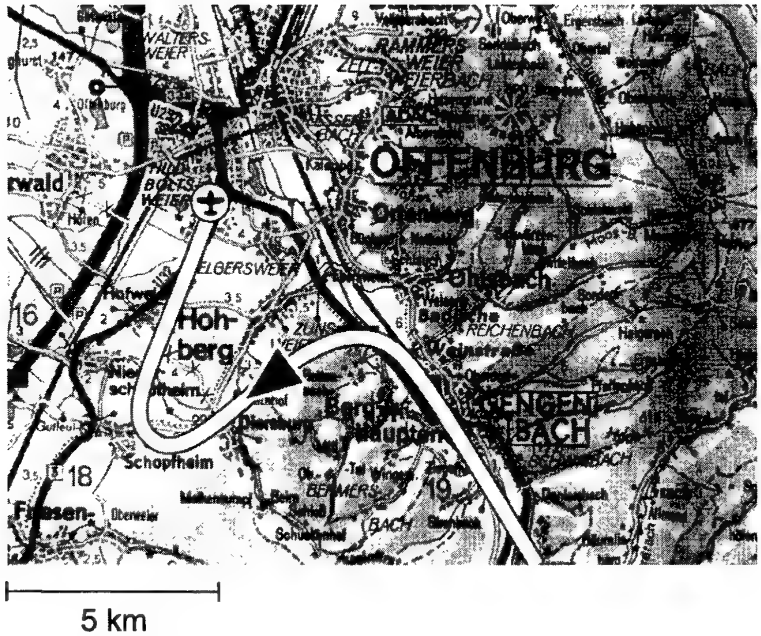


Fig. 21 Approach to Runway 03 at Offenburg airport

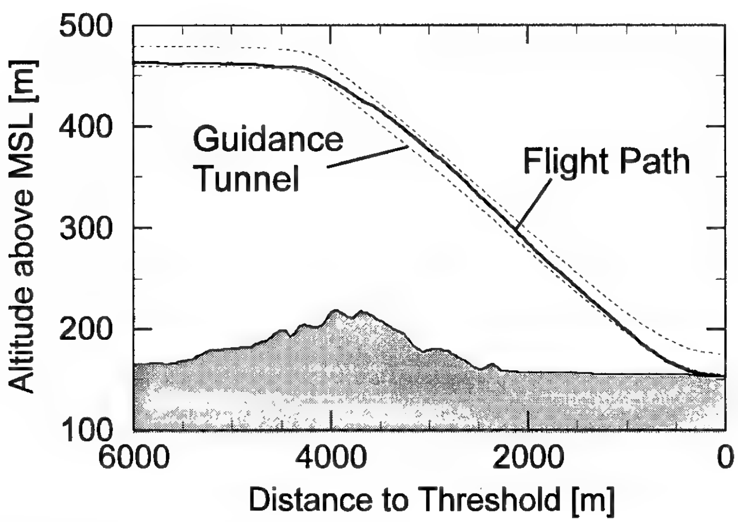


Fig. 22 Results from Offenburg/Schwarzwald test series

Validation of the Simultaneous Calibration of Aircraft Position Error and Airflow Angles Using a Differential GPS Technique on a Helicopter

Kenneth Hui Stewart Baillie
Flight Research Laboratory, Institute for Aerospace Research, National Research Council
Ottawa, Ontario, Canada K1A 0R6
Tel: (613)-998-9682 Fax: (613)-952-1704 E-mail: Ken.Hui@NRC.CA

1.0 SUMMARY

This paper describes the validation of a technique for the simultaneous determination of pitot-static position error and the calibration curves for angle of attack and sideslip sensors. The SCADS (simultaneous calibration of airdata system) technique involves flying the aircraft in a "wind box" pattern while recording a suite of standard flight test parameters and Differential Global Positioning System (DGPS) measurements. This simultaneous calibration technique combines the calibration procedure for both position error and airflow angle calibration, and eliminates the need for flying close to the ground during the tests. During the development of this technique using the NRC Falcon 20 aircraft, the results demonstrated that accurate calibrations could be obtained with reduced flight time and cost over conventional calibration techniques. The present paper describes the application of the SCADS technique to the NRC Bell 206B helicopter. The calibration results are presented and are compared with data from other standard calibration methods and verified with manoeuvres not used in the model development. The results from using the SCADS technique have demonstrated better efficiency and accuracy.

2.0 INTRODUCTION

CAE Electronics, Montreal, and the Flight Research Laboratory (FRL) of the National Research Council Canada (NRC) have conducted several joint programs to develop Level D flight simulators[1]. These programs have involved the use of a leased aircraft to gather the flight test data for the simulator mathematical model development. To minimize the cost of this and other projects, the FRL has concentrated on increasing the efficiency of the flight tests. One area of emphasis has been the development of a more efficient method of calibrating airdata systems.

The current FRL method of calibrating airdata systems is a two-step process. The first step is to obtain the position error correction (PEC) and flight data by:

a)-stopping at a reference position on a runway to record baseline position and pressure data;
b)-performing a single, low altitude fly-by down the runway to provide a single calibrated point of the airdata system; and
c)-performing a series of fly-bys over a relatively flat surface, such as a lake, to gather additional "pseudo-tower-fly-by" data.

The PEC coefficients are then determined using the flight data, as collected above, and the standard atmosphere equations.

The second step is to obtain the calibration curves for the angles of attack and sideslip; and the FRL flight path reconstruction (FPR) technique[2] is used for this purpose with a variety of flight test manoeuvres such as trim points and beta sweeps. This technique has been used successfully on flight test programs for several types of aircraft[3], and requires a fully calibrated airspeed system. Even though these methods of calibration have been proven to be accurate, they are tedious and complex. The two processes cannot be flown simultaneously, and the requirement to fly the test points in series results in additional flight test time and cost. The total flight test time required for this calibration is about five hours. Additional drawbacks of this technique are that the FPR process requires high accuracy inertial measurements and assumes the angle of sideslip to be zero during trim points. These drawbacks have led to a search for improved methods of calibrating airspeed and airflow angles.

Recent advances in the Global Positioning System (GPS), in terms of accuracy and price, have made it possible to use this system in the calibration of aircraft airdata systems. Other agencies have used GPS for airspeed calibration. Kimberlin[4] showed in 1992 that the use of GPS for the pitot-static system calibration gave results similar to the two conventional methods, namely the "Speed Course" and "Tower-Fly-By" methods. This project was conducted on the Princeton University in-flight simulator (a Ryan Navion aircraft).

FRL has developed a process based on GPS, error modelling and minimization techniques to calibrate airdata systems in a single step. This technique has been named SCADS (Simultaneous Calibration of Airdata System). Hui, Srinivasan and Baillie[5] showed in 1996 that the SCADS technique provided accurate results on the NRC Falcon 20 aircraft. The airdata measurements were obtained from a project-dedicated pitot-static system, while nosecone differential pressure ports provided angle of attack and sideslip measurements.

Future FRL plans include the requirement for numerous helicopter flight tests. With the recognition that the nosecone differential pressure technique is not applicable to helicopters, and that airdata measurement errors are more difficult to determine for helicopter than for fixed-wing aircraft, a validation of the SCADS technique on a helicopter with a noseboom installation was required.

This paper reviews the development of the airdata aerodynamic model algorithms, and the flight test manoeuvres for calibration using the SCADS technique, and focuses on the validation of the SCADS technique for helicopter applications. In particular, the paper will describe:

1) position error characteristics and calibration methods;
2) flow angle modelling for a noseboom installation;
3) effects of wind on airdata calibrations;
4) the SCADS technique and the specific details for the helicopter application;
5) the NRC Bell 206B and its instrumentation and
6) the results of a SCADS flight test on the NRC Bell 206B.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

3.0 POSITION ERROR CHARACTERISTICS AND CALIBRATION METHODS

Brown[6] has described that the flow field around an aircraft in flight is distorted and, in turn, the local static pressure usually differs from that at infinity. The magnitude of this error generally increases with speed in proportion to aerodynamic forces and compressibility effects, and is also strongly affected by the location of the pressure sensor source on the aircraft.

Gracey[7] showed that it is generally possible to design a pitot tube installation to avoid measurable total pressure error for typical flight conditions. As a result, to produce accurate airspeed and altitude data on most aircraft, a calibration is only needed for the static pressure source position error. References 6 through 10 discuss pitot-static calibration techniques, specific procedures and expected accuracies. Some references also include the analysis of airflow angle calibration methods. These methods include the ground speed course, trailing bomb, pacer method, tower-fly-by method and Radar techniques. These methods fall into three general categories, namely (1) the direct speed reference methods which depend on favourable wind conditions, (2) methods which do not require any special atmospheric measurements, and (3) radar methods using atmospheric measurements or meteorological analysis for the reference pressure altimetry.

4.0 FLOW ANGLE MODELLING

The vanes on the noseboom measure the angles between the local velocity vector and the noseboom axes. These two angles are defined in Etkin[11] as angle of attack and flank angle of attack. In this paper, the subscript of the noseboom was dropped for the angles of attack and sideslip, flank angle of attack and the true airspeed vector and its components.

Angle of attack: $\alpha = \tan^{-1}(w/u)$

Flank angle of attack: $\beta_F = \tan^{-1}(v/u)$

where u, v, w are the three components of the true airspeed vector while U is the magnitude of the true airspeed vector and

Angle of sideslip: $\beta = \sin^{-1}(v/U)$

Traditionally, flank angle of attack, β_F, is equated to angle of sideslip, β[12]; however, these two quantities are not exactly the same. Flank angle of attack is the rotation of the freestream velocity vector about the body Z axis. Angle of sideslip is the rotation of the freestream velocity vector about the stability Z axis. Corrections for the following must be applied to the measured angles α_m, β_{Fm}, to obtain the true angles of attack and sideslip: 1) noseboom misalignment, 2) noseboom bending, 3) upwash and sidewash, 4) transformation of flank angle of attack to angle of sideslip and 5) aircraft angular rate.

4.1 Noseboom Misalignment Corrections

The Bell 206B noseboom was installed with misalignments on the order of 0.1 - 0.3 degrees from the aircraft axis system. Fortunately, for misalignments of this magnitude, the significant terms in the axis transformation occur as minor biases and scale factor errors which may be implicitly included in the upwash/sidewash corrections to be discussed in an upcoming section.

4.2 Noseboom Bending Corrections

During elevated-g manoeuvring, the noseboom will deflect with the increasing load. For the wind box manoeuvre and most flight test manoeuvres of interest, the g-loading is either small or short-lived; therefore, the noseboom bending effect was ignored in this application.

4.3 Effects of Aircraft Induced Upwash and Sidewash

This is the aerodynamic effect that the helicopter and/or the noseboom induces on the local velocity vector. The vanes on a noseboom measure the effective angle of attack and flank angle of attack (α_m, β_{Fm}), not the free-stream angles of attack and sideslip (α, β). The difference between these angles is defined as the upwash or sidewash. To adjust the flow angle model for this difference let:

$$\alpha_m = \alpha + \Delta\alpha$$
$$\beta_{Fm} = \beta_F + \Delta\beta_F$$

For both α and β ranging between +/- 20 degrees, Moes and Whitmore[13] showed that the up- and side- wash correction terms for a wingtip boom mounted on a fixed-wing aircraft are:

$$\Delta\alpha = m\,\alpha_m + \alpha_{bias}$$
$$\Delta\beta_F = n\,\beta_{Fm} + \beta_{bias}$$

where m (upwash factor) and n (sidewash factor) are approximately constant at low speeds and less than 1.0.
With this as a basis, the vane calibration equations can be rearranged into the form:

$$\alpha = (1-m)\,\alpha_m + \alpha_{bias}$$
$$\beta_F = (1-n)\,\beta_{Fm} + \beta_{Fbias}$$

This form of correction will be assumed for the helicopter noseboom case presented here.

4.4 Transformation of Flank Angle of Attack to Angle of Sideslip

The transformation of the flank angle of attack to angle of sideslip is governed by the following equation:

$$\beta = \tan^{-1}[\tan(\beta_F)\cos(\alpha)]$$

For small angles of attack, less than +/- 10 degrees, the difference between β and β_F is minimal and, therefore, can be neglected. For larger angle of attack ranges, however, this nonlinear term must be included in the corrections.

4.5 Aircraft Angular Rate Corrections

Since the noseboom is not located at the aircraft centre of gravity, any aircraft angular rate will induce an additional airspeed at the vane location. The noseboom components of velocity must be corrected to the centre of gravity (CG) of the aircraft. These corrections are presented in detail in Reference 5. As an example, for a centreline-mounted α-vane, this correction is given by the equation:

$$\alpha_t = \tan^{-1}[(u\tan\alpha + Q\,x_i)/(u - Q\,z_i)]$$

where $u = U\cos\alpha\cos\beta$;
α_t is the true angle of attack at the CG of the aircraft;
x_i, z_i are the distances from the centre of gravity of the aircraft to the noseboom and
Q is the pitch rate of the aircraft.

5.0 EFFECTS OF WIND ON AIRDATA CALIBRATION

During a flight research program, Ehernberger[14] acquired and analyzed a set of wind variation data. These data indicated

that wind variations are often larger than airdata calibration accuracy standards (typically 0.003 Mach). Ehernberger's data showed typical variations in wind of 0.075 Knots/mile and typical RMS values of 6 Knots over a 3.5 hour time period. His results agreed reasonably well with wind variability determined from larger data sets produced by the National Meteorological Center and the USAF Global Weather Center.

Chan[15] did a similar study of a vertical wind. For turbulent flight, it was possible to have large excursions in vertical wind data (+/- 6 knots peak-to-peak in two minutes) during a 20-min session, with the vertical wind returning to a mean value (2 knots) after the perturbation. Chan also concluded that, for most of the flight, the atmosphere was smooth, and the vertical winds generally averaged zero over a long period of time. In consideration of the above data, the SCADS technique employs a wind model which can vary linearly with time.

6.0 THE SCADS TECHNIQUE

The purpose of the flight test manoeuvre in the SCADS technique is to create an aircraft time history for which the errors in the airdata system are independent of wind speed and direction. The standard method of eliminating the correlation between wind speed and pitot-static errors is to fly the aircraft on reciprocal headings. This approach does not, however, adequately discern errors in the measurement of sideslip angle. In the SCADS technique, therefore, the aircraft is flown in a wind box pattern (see Figure 1). To further produce variation in angles of attack and sideslip and, therefore, to improve the information content of the time history, variations in airspeed and beta sweep manoeuvres have been incorporated in the various "legs" of the wind box.

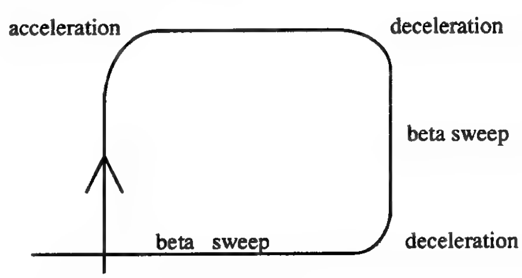


Figure 1 Typical Wind Box Pattern

According to the SCADS results from previous flight tests on the NRC Falcon 20[5], a wind box with an acceleration/deceleration manoeuvre in the first two legs of the wind box was better than a wind box flown at a single constant speed. In the present work, the requirement for a variation in airspeed over the SCADS manoeuvre was met by accelerating or decelerating the aircraft either on straight segments or during turns. For all wind boxes, a gradual sideslip change with constant track was executed in both directions (known as a beta sweep) on the third and last legs of the wind box. Each wind box covered the entire airspeed envelope of the helicopter. All wind boxes were performed within 25 km of the GPS reference station to maintain the optimum GPS measurement accuracy.

The general equations for SCADS were presented in Reference 5. Some of the equations specific to the SCADS application in helicopters will be listed below. The equations for the position error correction (ΔP), true dynamic pressure (P_d) and true static pressure (P_s) of the Bell 206B helicopter are approximated by:

$$\Delta P = C_{P0} + C_{P1} * P_{di} + C_{P2} * P_{di}^{\;2}$$
$$P_d = P_{di} + \Delta P$$
$$P_s = P_{si} - \Delta P$$

where

P_{di}, P_{si} are the indicated dynamic and static pressures.

The second order error term is uniquely used in this application on a Bell 206B. The helicopter up- and side-wash effects, as previously discussed in Section 4.0, 'Flow Angle Modelling', may be implicitly expressed in the vane calibration equations as:

$$\alpha = C_{A0} + C_{A1} * \alpha_m$$

$$\beta = C_{B0} + C_{B1} * \beta_{Fm}$$

where the terms C_{A0} and C_{B0} reflect the sum of biases from the misalignment of the noseboom plus the up- or side- wash effects. C_{A1} and C_{B1} are sensitivity factors, and α_m, β_{Fm} are the geometric or static angle of attack and flank angle of attack measures.

To summarize the SCADS technique, the following parameters were measured during the wind box manoeuvre:

- dynamic pressure, static pressure, 3 attitudes (θ, ϕ, ψ),
- total temperature, 2 noseboom vane deflections,
- 3 angular rates (P, Q, R), 3 GPS ground speeds (V_{GN}, V_{GE}, V_{GD}), and GPS altitude (Z_G).

The aircraft ground speed vector for the manoeuvre is calculated from the true airspeed vector and an assumed wind model. The Direct Search Complex Algorithm method[16,17] varies the coefficients of 1) the position error correction equations, 2) the airflow angle model and 3) the wind model in order to minimize the weighted sum of the errors between the GPS-measured ground speed vector and the calculated ground speed vector. The minimization also considers the difference between calculated pressure altitude and GPS-derived altitude.

7.0 AIRCRAFT DESCRIPTION

The validation of the SCADS technique was performed using the NRC Bell 206B JetRanger (see Figure 2). This aircraft is a single engine utility-type helicopter. The main rotor is a two-bladed, semi-rigid see-saw type. The main rotor blades are of all-metal construction of aluminum alloy monocoque type. The diameter of the main rotor is 33 ft 4.0 in and the length of the chord is 13 inches.

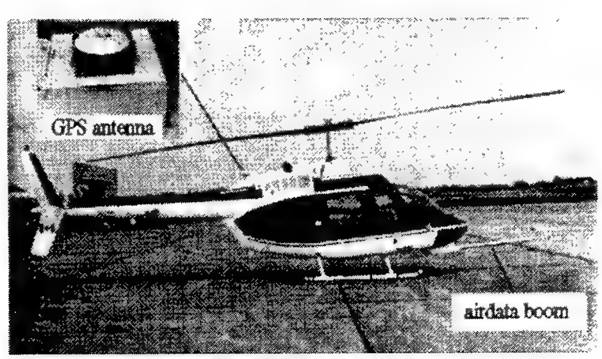


Figure 2 The NRC Bell 206 Helicopter

8.0 INSTRUMENTATION SYSTEM

For the SCADS validation project, a Litton LTN-90-100 Inertial Reference System (IRS) and the FRL high-accuracy portable instrumentation system and a data acquisition system (Micropak) were installed in the Bell 206B. This system included:

1) sensors for measuring the aircraft's inertial parameters,
2) a noseboom airdata system, with potentiometer measurements for the airflow angle vanes, and
3) a PC-mounted GPS receiver.

The time coded parameters were recorded onboard the helicopter at 64 Hz.

8.1 Inertial Parameters

Because the Litton IRS was designed for the navigation role on commercial aircraft, its parameters, especially normal accelerations, are heavily low pass filtered. For this reason, the measures of aircraft acceleration and angular rate were taken from the thermally-modelled accelerometers and rate sensors of the Micropak while attitude measures were obtained from the IRS.

8.2 Airdata System

Prior to this experiment, a swivelling pitot-static noseboom system, a Space Age Control, self-aligning airdata probe, was installed on the NRC Bell 206B helicopter for project purposes (Figure 3). The swivelling probe was separate from the pilot/co-pilot systems and consisted of a combined pitot-static tube with four fins attached to the end of the tube to allow for aerodynamic alignment of the probe with the local flow. There were six static orifices placed at 60-degree intervals around the tube. The swivelling probe was designed to align itself with the local flow to effectively eliminate total and static pressure losses as a result of local angles of attack and sideslip effects. The nose pitot section was mounted to permit a 21 degree swivel in any direction. Manufacturer's data suggests that the vanes can maintain their accuracy up to +/- 40 degrees of angles of attack and sideslip. The static and differential pressure transducers were ParoScientific "intelligent" transducers which are thermally modelled, and accurate to within 0.01 percent. A Rosemount total temperature probe was mounted vertically behind the sideslip vane and below the boom.

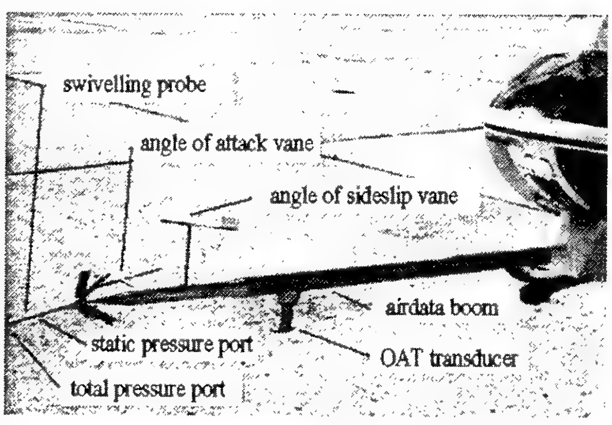


Figure 3 The Bell 206 Noseboom

8.3 Global Positioning System

A NovAtel 3151 GPS PC card receiver was installed in the test aircraft, with a model 511 antenna mounted atop the fuselage behind the main rotor of the helicopter. The unit was a single frequency (L1 at 1575.42 MHz) receiver card mounted in the backplane of a 486-computer system. The Differential mode of the GPS was used to obtain accurate measures of aircraft position and ground speed. The GPS reference station included a NovAtel 501 antenna with a choke-ring mounted atop the FRL hangar and a 3151 GPS PC card receiver. GPS data and status information could be displayed and controlled on either PC system by a NovAtel program called Winsat.

The GPS data post-processing software used ambiguity resolution and cycle slip handling techniques[18,19,20] developed by GeoNav System for single and dual frequency systems. For this experiment, with single-frequency observations, this GPS post-processing software, called P-RTK, was expected to generate its best accuracy for baselines (distance between the aircraft and the ground station) of 25 km or less. The combination of P-RTK and the NovAtel 3151 compatible receiver was expected to produce position accuracies of 2 cm + 2ppm (i.e., 2 mm error for every km) for fixed-wing aircraft[21] when at least four satellites were observed. The time-coded GPS data, processed with the P-RTK software, provided measures of longitude, latitude, height and the three components of velocity with respect to the ground. The WGS-84 convention was used to convert the longitude, latitude and height into local Cartesian coordinates.

The use of GPS in the helicopter environment is not as advanced as in fixed-wing applications. One problem for helicopters is that the rotor blades momentarily blank off the satellites. This blocking effect lowers the signal-to-noise level of the satellite measurements. With low signal-to-noise level, the occurrence of what are known as cycle-slips becomes more prevalent. These complications made the processing of helicopter GPS measurements more difficult.

At the beginning of the SCADS validation flights, the NovAtel GPS receiver was configured to track ephemeris and the satellite pseudoranges with options that were validated in previous fixed-wing studies. This setup resulted in GPS data which was unusable. Newer options for the NovAtel configuration were tried and much improved data resulted. Attention was also paid to the manner in which the helicopter was flown. High quality GPS data was finally achieved by using the newer configuration options and by flying the helicopter with the following limitations/procedures:

- Position the helicopter at a location where no obstacles block the signal from the satellites
- Set 100% Nr (rotor RPM)
- Start Winsat and wait until at least 4 satellites are tracked before starting the data log
- Collect 5 minutes of GPS data prior to moving the helicopter
- Climb to the test altitude gradually
- Limit turns to less than 40 deg bank and limit roll/yaw angular rates to less than 30 deg/sec
- Return to the starting location and, with Nr =100%, record 3 more minutes of GPS data.

All GPS data used in this paper were collected in the above manner and resulted in an integer ambiguity solution with no special user interaction.

9.0 SCADS FLIGHT TEST ON THE BELL 206B

The NRC Bell 206B SCADS flight test comprised 3.7 flight hours in 3 flights over a 3 day period. The objectives of this flight test were to optimize the SCADS manoeuvre for the helicopter application, to calibrate the Bell 206B airdata system using the SCADS technique and to assess the accuracy of that calibration by collecting and analyzing time histories of other types of aircraft manoeuvres. The following sections will summarize the results and discuss them in relation to these objectives. Wind conditions for the three flights are described in Table 1.

9.1 Summary of Results

The downwash from the main rotor clears the noseboom-vanes when the helicopter exceeds a forward speed of 20 Knots. Therefore, most of the SCADS wind box manoeuvres were performed within an IAS range of 40 to 110 Knots. The wind boxes were performed at altitudes of either 1000 ft or 5000 ft and in one of three wind conditions; calm, strong and steady, or moderate and turbulent. The SCADS-derived airdata calibration coefficients are presented in Table 1. The File designator indicates the wind conditions (i.e., S - Steady strong wind of 15 Knots, U - Moderate but turbulent wind of 7 Knots and C - Calm wind of 1.5 Knots). The Type designator indicates how the variation in airspeed was accomplished: L - Acceleration/deceleration within the first two legs of the wind box, T - the acceleration/deceleration within the turns and T2 - similar to T except the last leg has a different constant speed. All airdata calibration coefficients are relatively consistent in value. The values of the airdata calibration coefficients have the best agreement for calm wind cases. The predicted wind magnitudes for all cases agree to within 1-2 knots. The calculated wind direction is also relatively consistent. These wind magnitudes and directions also agree well with the actual and predicted weather measures over the Ottawa/McDonald Cartier International airport.

9.2 Comparison of Results from Different SCADS Manoeuvres

Inspecting the values presented in Table 1, with consideration of the acceleration/deceleration type, leads to the conclusion that the T2 manoeuvre type is slightly superior. Unfortunately, T2 manoeuvres were only flown in calm conditions; therefore, the comparison may be misleading. From a qualitative consideration of the more uniform distribution of angle of attack achieved during T2 manoeuvres it is felt, however, that the T2 manoeuvre is slightly superior to others.

9.3 Bell 206 Airdata Calibration

The airdata calibration coefficients for the Bell 206B are summarized in Table 2. These coefficients were sorted by meteorological wind conditions. The overall values reflect an average of airdata calibration coefficients which were derived from all the available cases. The range of deviations from the average value for the calm air condition group were significantly lower than for the other two groups. Under these conditions, the wind is more repeatable and the airdata coefficients are more robust. Based upon the consistency of the calm air coefficients and the wind data, on a case by case basis, the averaged calm air coefficients were chosen as the final NRC Bell 206B calibration. Note that this choice represents only 0.6 hours of flight data, including aircraft transit time.

Designators			Position Error Correction			α		β		Resulting Wind Model		
File	IAS Kt	Type	C_{P0} psi	C_{P1}	C_{P2} /psi	C_{A0}	C_{A1}	C_{B0}	C_{B1}	W_{n0} ft/sec	W_{e0} ft/sec	W_{dn0} ft/sec
S01	40-110	Lacc/dec	0.011	-0.067	0.637	0.403	0.887	-.559	0.964	24.93	-.79	1.41
S02	40-110	Lacc/dec	0.007	-0.045	0.759	0.181	1.049	-.573	0.981	25.85	.19	4.00
S03	60-110	Tacc/dec	0.013	-0.067	0.578	0.229	0.796	0.274	0.910	24.42	3.50	2.54
U01	40-100	Tacc/dec	0.012	-0.069	0.558	-.030	0.759	-.444	0.920	-.089	-9.91	2.08
U02	40-100	Tacc/dec	0.008	-0.060	0.864	0.134	0.661	-.446	0.914	-.048	-10.56	2.52
U03	40-100	Tacc/dec	0.008	-0.041	0.819	0.205	0.646	-.428	0.889	3.51	-11.54	1.64
U04	40-100	Lacc/dec	0.009	-0.061	0.987	0.523	0.823	0.820	0.927	6.36	-11.06	1.90
U05	40-100	Lacc/dec	0.008	-0.056	0.596	0.729	0.844	0.445	0.868	5.79	-12.14	1.12
C01	40-100	T2ac/dec	0.011	-0.042	0.661	0.625	0.734	-.230	0.899	1.64	-1.49	0.68
C02	40-100	T2ac/dec	0.010	-0.048	0.743	0.360	0.779	-.340	0.944	0.35	-1.44	1.73
C03	40-100	T2ac/dec	0.010	-0.048	0.772	0.648	0.724	-.166	0.898	0.35	-1.49	0.66

Table 1 Results from the Eleven Wind Box Manoeuvres

Group	C_{P0} psi +/- range	C_{P1} +/- range	C_{P2} /psi +/- range	C_{A0} +/- range	C_{A1} +/- range	C_{B0} +/- range	C_{B1} +/- range
Strong and Steady	0.0105 +/- 0.0025	-0.0597 +/- 0.0107	0.6579 +/- 0.0756	0.2711 +/- 0.0954	0.9106 +/- 0.1046	-0.2862 +/- 0.3961	0.9518 +/- 0.0301
Moderate and Turb.	0.0089 +/- 0.0014	-0.0574 +/- 0.0094	0.7647 +/-0.1632	0.3124 +/- 0.2750	0.7466 +/- 0.0812	-0.0106 +/- 0.5384	0.9035 +/- 0.0218
Calm	0.0100 +/- 0.0005	-0.0458 +/- 0.0031	0.7254 +/-0.0469	0.5443 +/- 0.1304	0.7457 +/- 0.0238	-0.2453 +/- 0.0718	0.9135 +/- 0.0215
Overall	0.0096 +/- 0.0018	-0.0548 +/- 0.0103	0.7249 +/-0.1273	0.3644 +/- 0.2322	0.7911 +/- 0.1072	-0.1498 +/- 0.4386	0.9194 +/- 0.0316

Table 2 Summary of Airdata Calibration Coefficients

9.4 Typical SCADS Identification Results

Figure 4 shows the typical error between the GPS-measured ground speed/altitude time histories and those calculated from a SCADS estimation, in this case run C02. The significant features of this plot are:

1) groundspeed and altitude errors are small during constant heading sections;

2) these errors are large during turns (turn data is not used in the SCADS minimization routine).

9.5 Verification of Bell 206 PEC Calibration with Standard Calibration Techniques

The Bell 206B was flown up and down the runway in calm air conditions at different speeds using a ground speed course (GSC) technique. The runway was 9651 ft long. The PEC coefficients derived from this method and those from the SCADS estimation are listed in Table 3. The large difference between the estimated PECs at the lowest airspeed is attributable to a decrease in accuracy in the GSC method at lower speeds. In such cases, a small variation in wind will cause a large percentage variation in the PEC estimate.

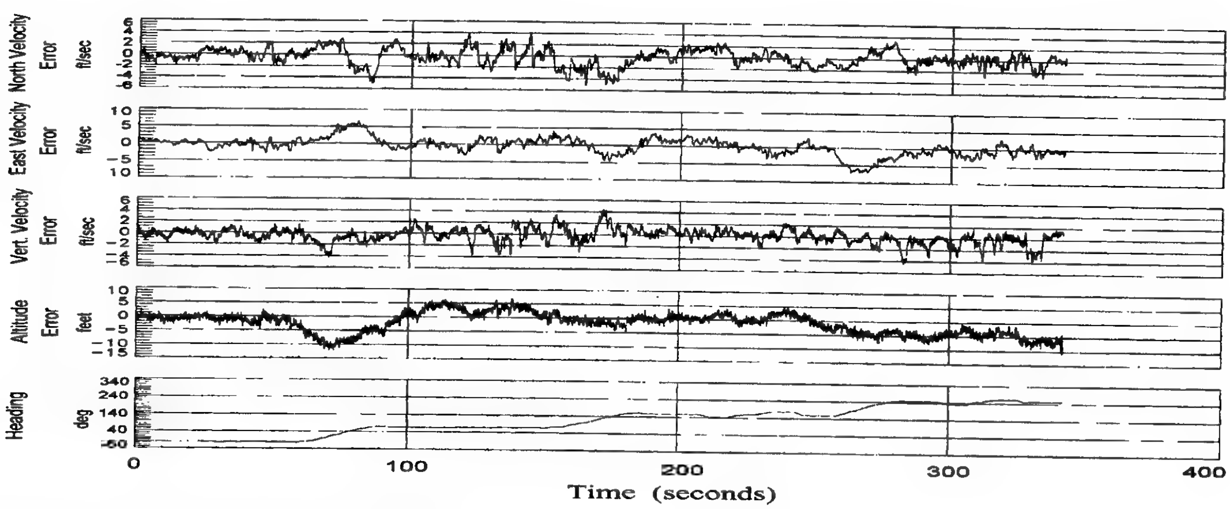


Figure 4 Typical SCADS Identification Results

Approximate IAS Kt	Avg Indicated Pd psi	GSC - PEC psi	SCADS - PEC psi	(SCADS-PEC) / P_d percent difference
40	0.02324	0.00545	0.00934	16.7
60	0.05310	0.00895	0.00962	1.26
80	0.09240	0.01428	0.01200	-2.47
100	0.16670	0.02063	0.02253	1.14

Table 3 PEC Coefficient Comparison SCADS Vs GSC

Case	Leg segment	Wind Magnitude ft/s	Wind Direction deg	North Wind ft/s	East Wind ft/s	Aircraft Heading deg
Calm	1	2.47	-34.3	1.16	-0.79	341.3
	2	2.61	6.9	1.33	0.16	68.3
	3	2.92	22.1	2.34	0.95	155.9
	4	3.82	30.6	2.57	1.52	246.7
Moderate	1	10.65	271.9	0.3	-10.5	337.0
	2	10.78	289.0	3.5	-10.0	70.3
	3	12.63	293.4	4.6	-11.5	160.7
	4	13.32	290.5	4.8	-11.9	250.5

Table 4 Two Cases of SCADS Results for PEC Verification

9.6 Verification with Flight Data

Verification of the SCADS-produced Bell 206B airdata calibration was performed by using flight records which were not used in the development of the PEC. Two cases were chosen: a constant airspeed wind box flown in calm wind conditions and a wind box with airspeed changes during the turns flown in moderate and turbulent wind conditions. For each of the manoeuvres, the SCADS-derived calibrations were applied to the airdata measurements, and the wind was determined from the difference between the measured/calibrated airspeed vector and the GPS-measured groundspeed vector. The mean value of the horizontal wind vector for each wind box leg gives an estimate of the accuracy of the airspeed. Table 4 shows these mean values.

Based on an inspection of Table 4 and a comparison of mean wind magnitudes and directions for reciprocal heading legs, the worst case airspeed error (assuming the actual wind was constant) is 1.27 ft/sec (0.75 Knots), derived from the moderate wind case in the second and fourth legs. This gives a conservative estimate of the PEC accuracy.

A second verification can be performed by inspecting the calculated wind for correlation with variations in angle of attack and sideslip. Figure 5 shows the wind components calculated during the Beta sweep of the calm air wind box. Figure 5 shows a minimal correction in calculated wind with β. Attributing all East wind variation (approximately equivalent to body axis lateral wind) to errors in the β calibration results in a worst case β error of 0.21^0 over the range of +/- 13.5^0. A similar look at vertical wind variation correlated to angle of attack change produced a maximum angle of attack error of 0.31^0 over a range of +/- 3.5^0.

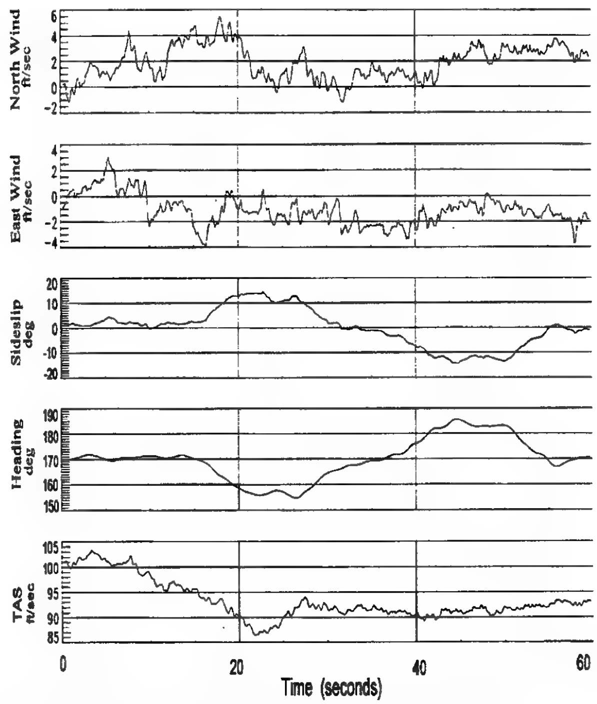


Figure 5 A Beta Sweep Leg-of a T2 Type Wind Box

10.0 CONCLUSIONS

A simultaneous calibration of the airdata system (SCADS) technique was validated using the NRC Bell 206B helicopter. Flight test results from the SCADS technique were compared to other standard calibration methods and matched well. The following specific conclusions can be reached:

- Calm weather conditions are preferable for the calibration of a helicopter airdata system.
- The SCADS technique provides better efficiency and accuracy than previous FRL methods.
- The SCADS method provided an airspeed calibration to within 0.75 Knots, and airflow angle calibrations to within 0.31^0 for α and 0.21^0 for β.

The aircraft instrumentation included a swivelling pitot-static noseboom with airflow vanes, a NovAtel DGPS and inertial sensors. The aircraft was flown in a wind box pattern with gradual beta sweeps and in an acceleration/deceleration fashion. The initial airdata aerodynamic model was devised from the empirical formulation based on the position error characteristics, noseboom airflow modelling, and atmospheric analysis for an airdata calibration. The SCADS technique allowed a simple and accurate calibration of aircraft PEC and airflow angles. This technique was validated by modelling the Bell 206B helicopter airdata system in the IAS range of 40 to 110 Knots.

11.0 ACKNOWLEDGMENTS

We wish to acknowledge the contributions of Stephan Carignan, pilot of the NRC Bell 206B helicopter, who performed and developed the flight test procedures which ensured an integer ambiguity solution for the GPS.

12.0 REFERENCES

[1]Baillie, S. W.; Hui, K.; de Leeuw, J.: The Flight Test and Data Analysis Program for the Development of a Boeing/de Havilland Dash 8 Simulator Model. AGARD CP 519, Paper 30, May 1992.

[2]Hui, K.; Baillie S. W.; de Leeuw, J. H.: The Application of Parameter Estimation to Identify the Aerodynamic Derivatives of the Dash 8 Series 100. CASI FTS, Ottawa, Ontario, May 1992.

[3]Srinivasan, R.; Hui, K.; Baillie, S. W.: Airflow Angle Measurement Using a Multi-hole Radome Differential Pressure Technique. CASI Journal, Vol 41, No. 4, December 1995.

[4]Kimberlin, R. D.; Sims, J. P.: Airspeed Calibration Using GPS. University of Tennessee, Space Institute, Tullahoma, TN, AIAA 92-4090, August 24-26, 1992.

[5]Hui, K.; Srinivasan, R.; Baillie, S. W.: Simultaneous Calibration of Aircraft Position Error and Airflow Angles Using Differential GPS. CASI FTS, Ottawa, Ontario, Canada April 1996 (submitted for CASI Journal publication, December 1996).

[6]Brown, E. N.: Position Error Calibration of a Pressure Survey Aircraft Using a Trailing Cone. National Center for Atmospheric Research, Technical Note NCAR/TN-313+STR, Boulder, CO., July, 1988.

[7]Gracey, W.: Measurement of Aircraft Speed and Altitude. NASA RP-1046, 1980.

[8]DeAnda, A. G.: AFFTC Standard Airspeed Calibration Procedures, AFFTC-TIH-81-5, Edwards Air Force Base, CA, June 1981.

[9]Lawford, J. A.; Nippress, K. R.: Calibration of Airdata System and Flow Direction Sensors. AGARD-AG-300, Vol. 1, Sept. 1983.

[10]Haering, E. A. Jr.: Airdata Calibration of a High-Performance Aircraft for Measuring Atmospheric Wind Profile. NASA TM-101714, 1990.

[11]Etkin, B.: Dynamics of Flight Stability and Control. Second edition, John Wiley and Son, 1982.

[12]Richardson, N. R.; Pearson, A. O.: Wind Tunnel Calibration of a Combined Pitot-Static Tube, Vane-Tube Flow-Direction Transmitter, and Stagnation-Temperature Element at Mach Numbers from 0.60 to 2.87. NASA TN D-122, 1959.

[13]Moes, T. R; Whitmore, S. A.: Preliminary Look at Techniques Used to Obtain Airdata from Flight at High Angles of Attack. NASA TM-101729, December 1990.

[14]Ehernberger, L. J.; Haering, E. A. Jr.; Lockhart, M.G.; Teets, E. H.: Atmospheric Analysis for Airdata Calibration on Research Aircraft. AIAA 92-0293, NV., January 6-9, 1992.

[15]Chan, K. R.; Bowen, S. W.; Scott, S. G.; Bui, T. P.: The NASA ER-2 Meteorological Measurement System: Instrumentation, Calibration and Intercomparison Results. Appendix B.6 J. Geophys. Res., 94, 11573-11587, 1989.

[16]Anon: Internal Mathematical Software Library (IMSL), Version 1.0, April 1987.

[17]Gill, P.E.; Murray, W.; Wright, M.H.: Practical Optimization. Academic Press, New York, 1981.

[18]Chen, D.: FAST Ambiguity Search Filter (FASF): A Novel Concept for GPS Ambiguities Resolution. Proc. Of GPS'93, The Institute of Navigation, Alexandria, VA, pp. 781-787, 1993.

[19]Chen, D.; Lachapelle, G.: The Comparative Analysis of FASF and the Least-Squares Ambiguity Resolution Technique. Proc. Of KIS'94, Dept of Geomatics Engg., Calgary, AB., 1994.

[20]Chen, D.: Performance Outline of P-RTK. Internal documentation of GeoNav Systems, Calgary, Alberta, Canada, 1994.

[21]Croll, J.B.; Lochhead, H. M.; Liu, J.: Flight Validation of the Position Accuracies of a NovAtel RT-20 Differential GPS Installed in a Falcon 20 Aircraft. Canadian National Research Council, LTR-FR-130, May 1996.

FOREBODY VORTEX CONTROL

Dr. Lawrence A. Walchli
Dr. David J. Moorhouse

Wright Laboratory, WL/FFI
Wright Patterson AFB, Ohio 45433
USA

ABSTRACT

Much attention has been focussed in recent years on tactical maneuvering in post-stall flight. Such programs as the X-31, VISTA/MATV, and the X-29A have established that tactical supermaneuverability at very high angles of attack (AOA) is a potent offensive weapon provided that the adversary can be enticed into close-in combat. Never before have requirements for integrating the pilot and aircraft been so important. The aircraft must have robust control authority in all axes, plenty of excess thrust, and pilot-friendly controls which allow him to fly to the limits of both his and the aircraft capability.

Modern fighter aircraft operating above about 25° AOA encounter a destabilizing phenomena caused by the complex three-dimensional separated vortical flowfield surrounding it. It is in this same region of flight that the aircraft wings and fuselage begin blanking the rudder, resulting in both degraded directional stability and control authority. Hence, two requirements emerge; increase directional stability and increase directional control authority. Thrust vectoring has been demonstrated as a means to increase control authority at all angles of attack. A potential way to increase directional stability could be by controlling the forebody vortex flow.

The primary object of this paper is to document an attempt to increase the directional stability of an F-16 aircraft at all angles of attack into the post-stall regime. A wind tunnel test program had previously shown beneficial effects of forebody chines; additional testing provided stability and control data to support a flight test program. Flight tests were conducted with and without chines as a small adjunct to a program investigating thrust vectoring to very high angles of attack, the F-16 VISTA/MATV program (Reference 1).

Specific maneuvers up to C_{Lmax} (and beyond) were assessed to determine the major effects of forebody chines, although parameter identification was not an objective of the program. This paper describes the results of this effort.

INTRODUCTION

Some sort of passive directional stability device has been examined or utilized on virtually all high performance fighters. Wright Laboratory has conducted extensive research on passive devices on the F-16 in recent years. Forebody chines have been examined in ground tests which improve the F-16 static

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

directional stability through 60° AOA. Simon, LeMay and Brandon conducted a test of the several chine configurations shown in Figure 1, extracted from Reference 2. These were tested on a 0.15 scale model in the NASA Langley Research Center 30x60 Foot Wind Tunnel. Figure 2, extracted from the same reference, suggests that Chine 7m forces symmetric separation of the forebody vortices which helps keep the aerodynamic forces and moments symmetric. Directional stability is improved above 25° AOA.

To validate these ground-based test results, Wright Laboratory initiated a flight test program for the forebody chines. The F-16 which was currently available for testing this technology was the F-16/VISTA/MATV, a program to evaluate high-angle-of-attack characteristics using thrust vectoring. Selection of this aircraft necessitated a wind tunnel test program designed to acquire the data needed to support this specific configuration (flight test noseboom and fuselage dorsal fairing).

WIND TUNNEL TEST PROGRAM

A 1/9 scale F-16/VISTA model was tested in the Lockheed Fort Worth Company Low Speed Wind Tunnel in San Diego, California. The test examined the static stability characteristics of three different chines. Two of these chines, 7 and 7m, represented the most promising configurations found in the test of Reference 2. The third, Chine 8a, was the same as Chine 7m, but extended forward to fit the longer flight test nose boom. Lateral and directional stability derivatives $C_{l\beta}$ and $C_{n\beta}$ for the chined configurations are compared to the baseline without a chine in Figure 3 for the sideslip range $0 \leq \beta \leq 4$ in the stability axis system. A significant improvement in directional characteristics is noted above 25° AOA for the chines. Chine 8a improves $C_{n\beta}$ at all angles above 25°. Both chines degrade lateral stability at small sideslips in this region. Neither showed an effect on the pitching moment characteristics of the aircraft.

FLIGHT TEST PROGRAM

The overall objective of the flight test phase of this program was to evaluate the effectiveness of nose chines on the stability and control characteristics of the F-16 VISTA/MATV aircraft. The availability of this specific aircraft for the chine flight test was a good news/bad news situation. The good news was that this F-16 was not restricted by an angle-of-attack limiter and could fly comfortably to maximum lift and on into post-stall. The bad news was that this capability came from adding the multi-axis thrust vectoring nozzle. High angle-of-attack control laws were integrated directly into the baseline F-16 control law structure. Blending aerodynamic and nozzle control power was transparent to the pilot. However, separating the chine aerodynamic effects from the nozzle effects was impossible. The resulting data analysis was qualitative in nature.

Based on wind tunnel results, Chine 8a was selected for evaluation. It was considered to have the most substantial positive effect on static directional stability. It did, however, cause some degradation of lateral characteristics.

For the purpose of this paper, two specific flight maneuvers were selected to investigate the effects of the chines - the *Slow Alpha Sweep* and the *Wings Level Sideslip Release.* The flight data from both maneuvers was assessed to derive the essential effects of the chines on the aerodynamics, both static and dynamic.

Slow Alpha Sweep (SAS):

Conditions - Full Military Power; standard flight control system (FCS); flight 92, maneuver 11(FLT9211)(chine on) and flight 94, maneuver 7 (FLT9407) (baseline); FLT9211 was flown at the pilot's discretion, FLT9407 was flown with the pilot out of the loop (both flights, same pilot); SAS assumed quasi-steady state; and the maneuver start time has been manipulated to align alpha ranges.

Results - The angle-of-attack sweeps and corresponding longitudinal stick inputs are shown in Figure 4. Figure 5 shows the pitch nozzle activity for the two configurations and Figure 6 shows the pitch rate for each. Note that the longitudinal stick activity for the two test points reflects the piloting philosophy described under "conditions" above. At the beginning of sweep, the baseline configuration displayed a somewhat higher stick force and pitch rate in comparison to the chined forebody results, and yet suffered a decrement in alpha dot. This decrement resulted from the flight conditions during entry and conduct of the test point. The chine data was acquired during descent while the baseline data was acquired during ascent. Taking this difference into account, the conclusion reached is that at low to moderate angles of attack, the chines had no influence on the pitching moment characteristics of the airplane. This conclusion verifies the wind tunnel test data discussed in the previous Section.

The baseline configuration shows a significant increase in alpha dot, starting at about 32° AOA. The stick force and nozzle position show slight changes in that direction but not commensurate with the change in aircraft motion. (A review of all of the control surfaces shows that the pitch nozzle is responsible for maneuvering in the longitudinal axis in this alpha range). Explanation of this abrupt change is complicated by the fact that the flight control system switches angle-of-attack input from the noseboom value to the Inertial Navigation Unit value in this same alpha range. This likewise is not expected to be responsible for the large difference shown here, although the effect will vary from maneuver to maneuver. The strong indication is that this large pitch acceleration at 32° alpha is an aerodynamic phenomenon, resulting from a forebody vortex/airframe interference that is suppressed by the forebody chines all the way to maximum trimmable angle of attack. We rule out the possibility of inertial coupling with the lateral/directional axes, because there is no inflection in the alpha trace at 50° AOA as roll and yaw reverse directions. The effect is most likely aerodynamic, but wind tunnel testing showed no such effect.

Between about 50° and 60° AOA, the baseline configuration ran out of airspeed and ascending flight transitioned to descending. Motion cues seduced the pilot into quickly pulling

full aft stick. The aircraft stabilized at about 73° AOA. Both configurations exhibited similar performance above 60° angle of attack in the longitudinal axis. Pitch oscillations were very similar, although longitudinal stick was constant for the baseline configuration. Thus, the oscillations appear to be a result of similar coupling with the lateral/directional axes as the aircraft experienced wing rock, with no appreciable difference due to the chines.

The lateral/directional results are summarized in Figures 7 and 8. Again, the lateral stick activity for each configuration reflects the piloting philosophy described above. The response of the baseline configuration (Figure 7) indicates that at angles of attack up to about 32°, there is very little coupling between roll and sideslip. Although the roll angle builds to 10° left wing down, the sideslip on the aircraft remains near zero. The bank angle begins to diverge around 30° AOA, peaks at about 45° and begins to return toward a wings level position. At 36° AOA, the nose of the aircraft briefly reverses direction. This is interpreted to be a nose vortex asymmetry reversal with a very narrow bandwidth, a condition experienced on other high-angle-of-attack flight vehicles such as the X-29A (Reference 3). By about 39° AOA, the nose resumes sliding to the right, and a sideslip oscillation begins which continues through the remainder of the maneuver. As the aircraft stabilizes at the target maximum trimmable angle of attack (about 73°), the bank angle gradually couples with the well-defined sideslip oscillation without lateral stick input. This motion is an example of the classical high angle-of-attack wing rock, a velocity vector rolling motion. As AOA is reduced at the end of the maneuver, there is the indication of another roll divergence.

For the chined configuration (Figure 8), there is a similar tendency for bank angle to diverge, starting just above 30° AOA. On this flight the pilot used lateral stick aggressively to minimize the excursions. When the vortex asymmetry reversal occurred at 36°, he quickly centered lateral stick. This stick activity may have effectively masked the asymmetry reversal which was clearly evident on the clean nose configuration. In the 40-45° range, he was able to manually dampen the chined nose motion, but quickly fell out of sync with his stick input. Coupling between roll and sideslip appeared strong between 30° and 40°, somewhat weakened between 40°and 55° AOA, but was strong again above 55° AOA. In general, addition of the chines did not alter the frequency of wing rock above 40° AOA. Once the natural motion stabilized above 55°, the amplitude of the motion was significantly reduced. With the pilot still aggressively trying to manually suppress the wing rock, it is difficult to sort out whether the reduced amplitude is an effect of adding the nose chines or is a result of the control command inputs.

Figure 9 shows roll angle versus sideslip angle at maximum trimmable angle of attack for each configuration. In this alpha range, roll and sideslip are strongly and equally coupled for both cases as is indicated by the parallel traces. This "pseudo-phase plot" shows a bounded oscillation between a beta of -15°

to +10° and a roll angle of -8° to +20° for the baseline configuration. With chines, the parameters vary between a beta of -2° to +12° and a roll angle of -18° to +1°. The approximate 50% reduction in movement between the two configurations could be aerodynamic effects from the chines or a result of the command inputs from the pilot. Both configurations exhibit neutral lateral/directional stability since both oscillate about non-zero roll and sideslip angles. This condition at maximum trimmable angle of attack is unconfirmed by wind tunnel data which was only acquired to 60° AOA.

Summary - Four significant findings have been gleaned from the data analysis for the slow alpha sweep. First, the chined forebody appears to suppress an undesirable vortex/airframe interaction above about 32 degrees angle of attack, resulting in smoother pitch performance at zero sideslip. Second, addition of nose chines on the F-16 contributes measurably to roll-yaw coupling in the low to moderate angle-of-attack range. Third, in the range of primary interest in this paper (AOA up to maximum lift), addition of nose chines does not eliminate vortex asymmetries, but rather seems to intensify the effects of them in the lateral/directional axes. And finally, above 55 degrees angle of attack, the chines may have significantly reduced the amplitude of wing rock.

Wings Level Sideslip Release (SSR) (performed at 30° and 45° AOA):

Conditions - Full Military Power; standard FCS; FLT9236 and FLT9240(chine on) and FLT9425 and FLT9428(baseline); 30 and 45 degrees target angles of attack; a dynamic maneuver; and the start time has been manipulated to align the pedal releases.

Results for 30° AOA (right rudder input) - Right rudder was applied to generate a large negative (nose right) sideslip. After achieving a steady state beta, the rudder pedal was returned to a zero input condition in one to two tenths of a second (Figure 10). The results, in terms of sideslip angle, are shown in Figure 11. The initial steady state conditions show that full pedal input produced about 19 deg on the chined configuration and 9 deg on the baseline configuration. In isolation, this would indicate that the chined configuration has less than 50% of the baseline directional stability. There are major differences between the two maneuvers, however, in terms of lateral stick input and bank angle, plus the various feedback loops produce different control positions. Examples are shown in Figure 12. In the absence of a formal parameter identification effort, the flight results were analyzed using the predicted stability and control derivatives from the VISTA simulation model. This has not been updated with flight test results, but provides a basis with which to determine accurate trends. Although not an explicit part of the maneuver, pilots tried to maintain heading so that we assume the sum of yawing moment contributions is zero. For the baseline configuration, the measured states and control positions with the VISTA stability and control derivatives allowed the calculation of yawing moment coefficient due to thrust vectoring - considered to be the most uncertain quantity. For the chined con-

figuration, it was assumed that only the directional stability was affected. This value was calculated from a similar balance of all the yawing moment contributions. The result was that the chined configuration had approximately 70% of the baseline directional stability, contradicting the increase that was predicted in the wind tunnel data. An analogous procedure on the rolling moment balance showed that the strong baseline dihedral effect was changed to the opposite sign (approximately a 125% reduction). The wind tunnel data in Figure 3 does indicate a reduction, but of less magnitude.

Following the rudder pedal release, Figure 11 shows that sideslip angle starts approaching zero for both configurations. The crisp sideslip response is accompanied on the baseline configuration by a stop in the slow rolling motion followed by a slow return to wings level, supported by lateral stick inputs. For the chined configuration, the lateral stick is neutralized as the rudder pedal is released. Even though sideslip angle is reducing, the large negative value produces a roll left wing down, consistent with the preceding discussion of the dihedral effect with chines. The roll continues diverging until the pilot arrests it with a lateral stick input. The appearance of a more-sluggish sideslip response for the chined configuration in Figure 11 must be caused by the roll motion from the dihedral effect. Returning to the baseline configuration, lateral stick is constant for the first 2 seconds and the aircraft exhibits a slow positive roll rate. This is consistent with the negative sideslip angle and the previously discussed dihedral effect. After the pedal release, the transition from negative to positive sideslip is also consistent with stopping the roll and returning to wings level (although the pilot also keeps lateral stick in to aid in this recovery).

Summary - The 30° AOA sideslip release maneuver showed that, in contrast to the wind tunnel data, the addition of nose chines on an F-16 forebody actually decreased directional stability. The maneuver also showed that, like the slow alpha sweep, coupling between the lateral and directional axes is significantly altered by the addition of the chines.

Results for 45° AOA (left rudder input) - The test point chosen for the 45° AOA dynamic maneuver clearly exemplifies the complexity of post-stall flight. Unlike the steady initial conditions at 30° AOA, the post-stall test point for the baseline configuration had to begin under somewhat changing conditions since the aircraft was already in significant wing rock. The pilot input less than full rudder in setting up the test point. To hold a steady-heading sideslip during wing rock, he countered his rudder input with opposite stick input. Since rudder effectiveness at 45° AOA is greatly reduced, the flight control laws are mechanized to use yaw nozzle to augment rudder. The baseline data show that with rudder and lateral stick held constant (but in opposite directions) a significant uncoordinated velocity vector roll persists. The yaw nozzle is attempting to reverse this wing rock. The first reaction to rudder release is a yaw nozzle reversal to counter the rudder-induced accelerations. As discussed previously, the pilot

remains out of the loop for the baseline maneuver. But as the velocity vector roll continues, the yaw nozzle again automatically counters and finally succeeds in stopping it. In general, the relative "baseline" data for 30° and 45° indicates similar roll/yaw movements commensurate with control inputs.

Examination of the data from the chined configuration test points shows significant differences in lateral/directional characteristics at the different angles of attack. The test point setup at 45° AOA reflects the effectiveness of chine addition through the significant reduction in wing rock described in the Slow Alpha Sweep maneuver (although there the reduction was most noticeable at 55° AOA and above). The chine addition also suggests that at 45° AOA, aircraft directional stability has increased in comparison with the baseline configuration until it is nearly neutral. This agrees fairly well with the trends established in the wind tunnel. Rudder input is less effective in generating sideslip and yaw nozzle deflections are somewhat less.

Summary - The 45° AOA sideslip release maneuver produced results similar to those predicted by wind tunnel data. Adding nose chines increased directional stability and decreased wing rock. Further, the strong dihedral effect seen at lower angles of attack actually decreased at 45° AOA until it apparently washed out. A significant variation in aircraft roll showed no discernable coupling into the directional axis.

CONCLUDING REMARKS

The flight test data showed an apparent significant effect of the forebody chines on pitching moment. Below 30° AOA, adding chines to the F-16 nose seemed to make little difference on the pitching moment. At approximately 32°, the baseline configuration showed a sharp increase in the pitch rate by a factor of ten, whereas the chine configuration showed a relatively smooth increase up to the target AOA. The strong indication was that it was an aerodynamic phenomenon. A possible explanation for this large change is that the pitch break in the baseline response is caused by forebody vortex/airframe interference that is suppressed by the effects of the chines.

The effects of the chines on the lateral/directional characteristics of the F-16 were also examined in flight. The results were a mixed bag. Asymmetries persisted, were even exacerbated by the chines in the alpha range to maximum lift. On the other hand, the chines produced a fairly strong roll-yaw coupling which could be beneficial for producing coordinated rolls. Further, as was the case with other chined configurations such as X-29A and X-31, wing rock under post-stall conditions was noticeably reduced.

The dynamic maneuver which was analyzed at two angles of attack showed that the chined forebody was decidedly less stable directionally than the baseline F-16, contradicting the 30° AOA wind tunnel data; at 45° AOA improvements in stability were achieved as predicted by the wind tunnel data. The loss in dihedral effect indicated by the wind tunnel data was actually far greater in flight at angles of attack below maximum lift. In post-stall, the dihedral effect washed out. It must be

emphasized that these results are to be taken as tentative trends. A more detailed parameter identification analysis is required.

Finally, the authors would like to acknowledge the assistance of Cal Dyer, VISTA Chief Engineer, in supplying the VISTA stability and control derivatives.

REFERENCES

1. Small, L. and Bonnema, K., "F-16 Multi-Axis Thrust Vectoring (MATV) Program Lessons Learned", AIAA Paper No. 94-3362, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 1994.

2. Simon, James M., et. al., "Results of Exploratory Wind Tunnel Tests of F-16/VISTA Forebody Vortex Control Devices", WL-TR-93-3013, January 1993

3. Moorhouse,D., Walchli, L. and Krumenacker, J., "Results and Lessons Learned from Two Wright Laboratory Flight Research Programs," AIAA-93-3661 August, 1993.

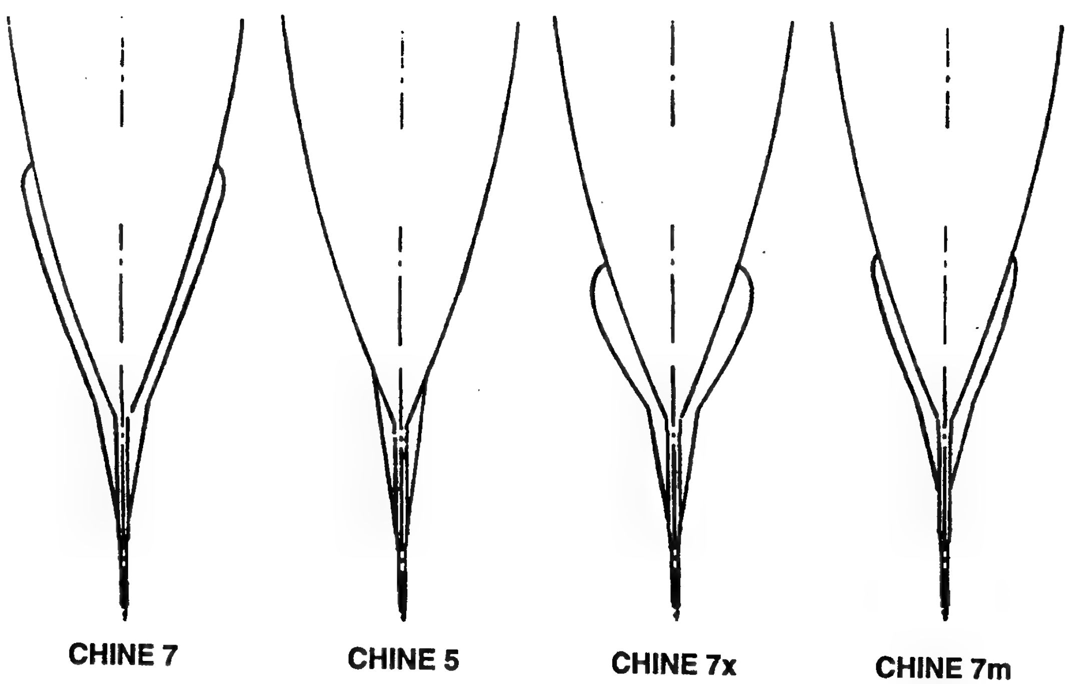


Figure 1: Comparison of Forebody Chines

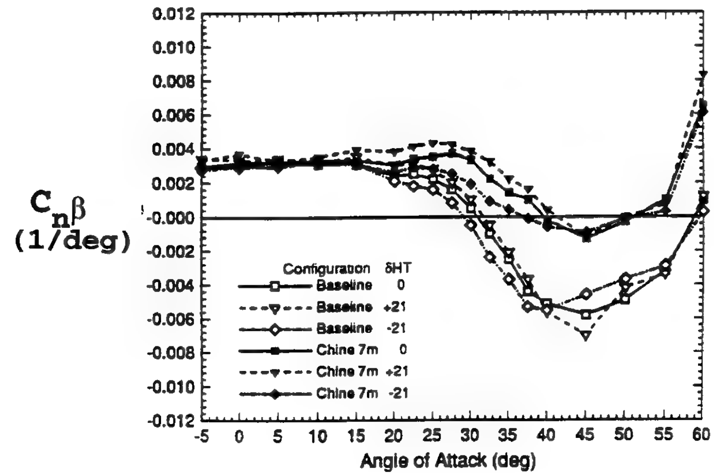
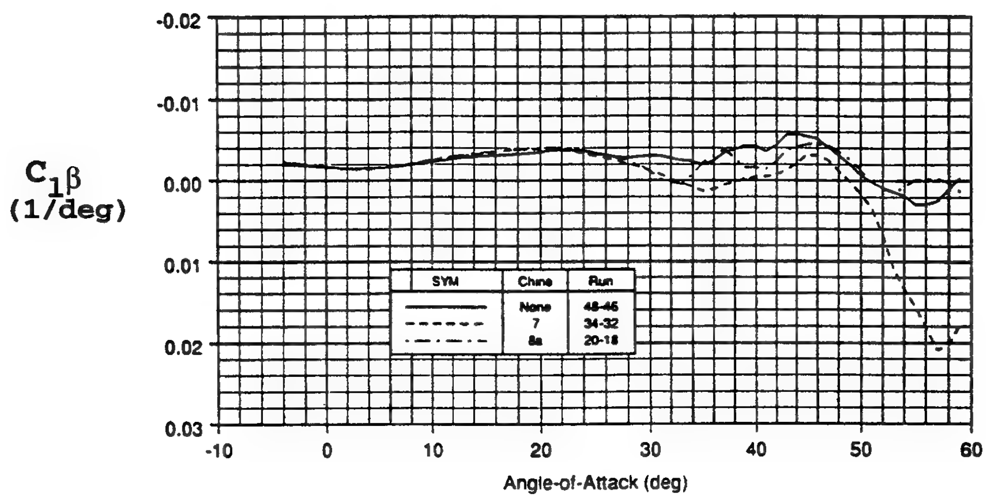


Figure 2: Effect of Chine 7m



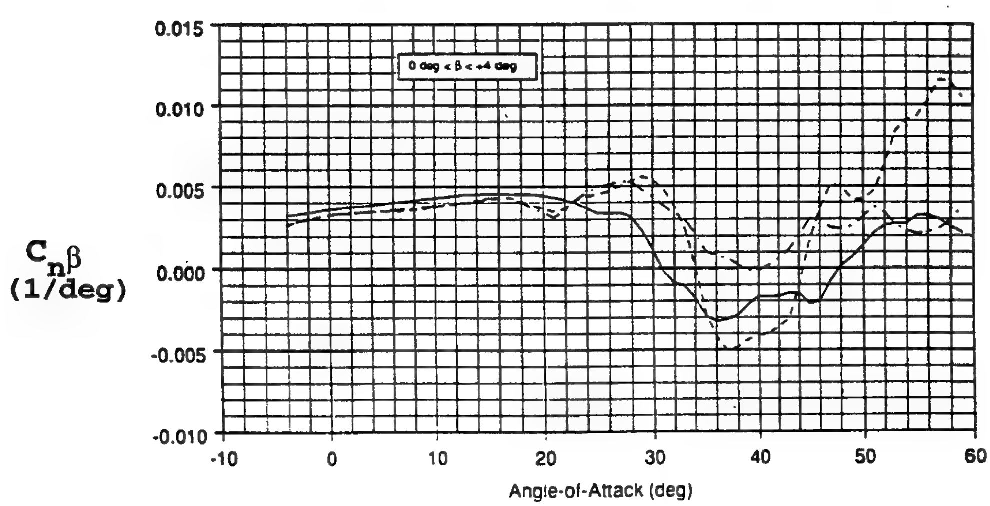


Figure 3: Comparison of Lateral/Directional Stability of Chines 7 and 8a with HT=0 for 0<β<4, LEF=25

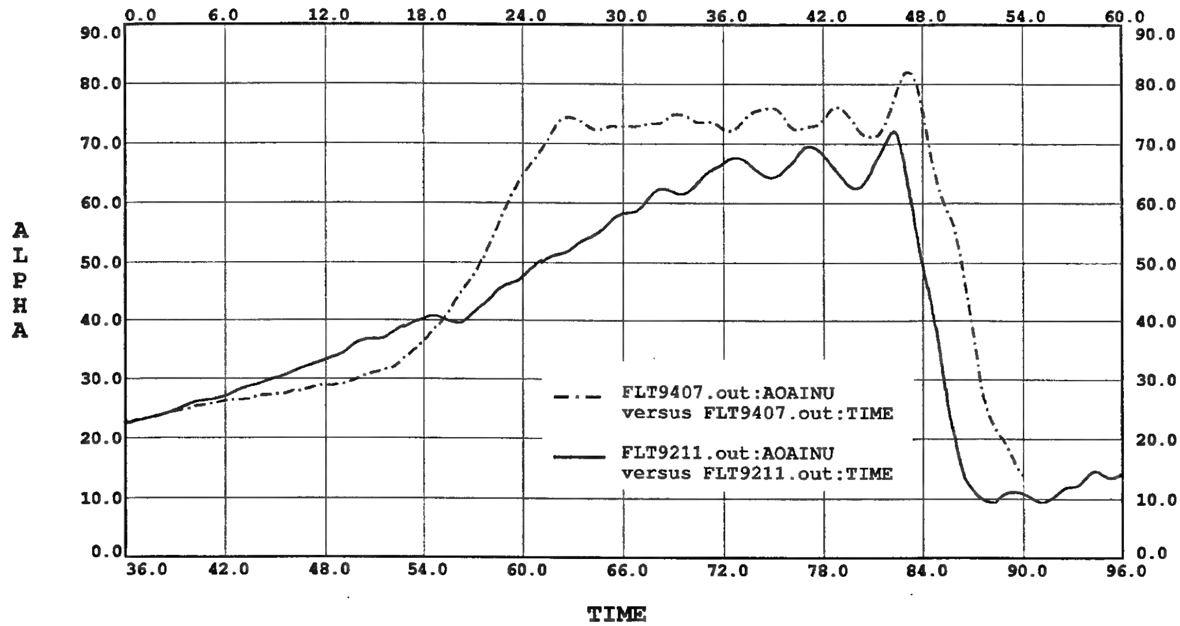


Figure 4a. SAS-FLT9211 & FLT9407-Alpha vs. Time

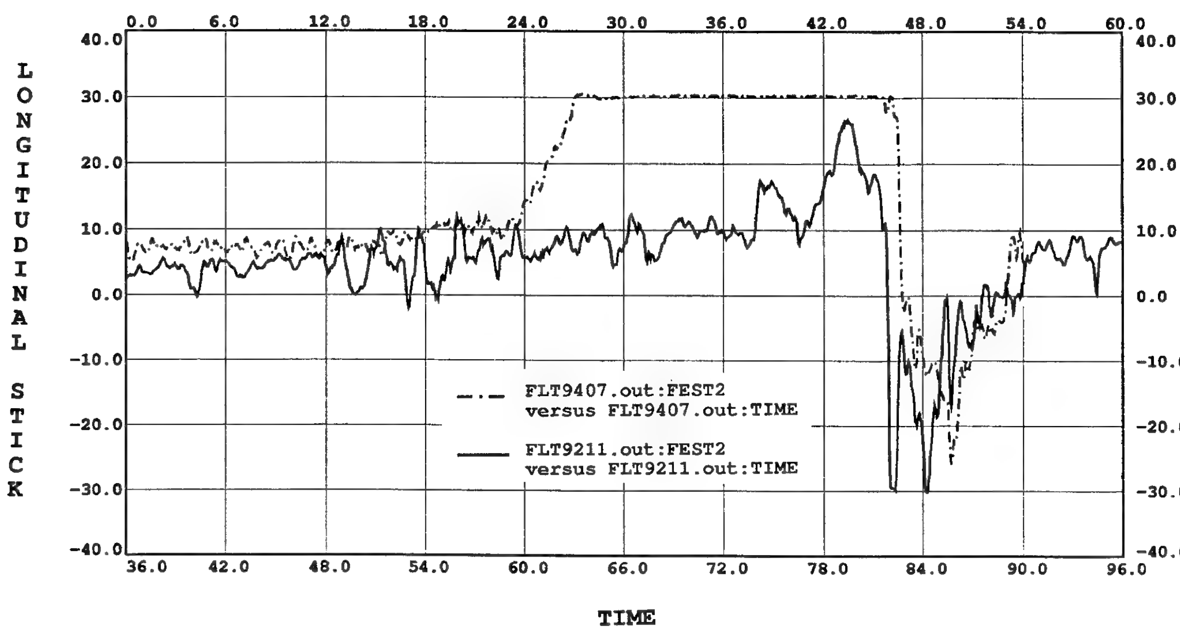


Figure 4b. SAS-FLT9211 & FLT9407-Longitudinal Stick vs. Time

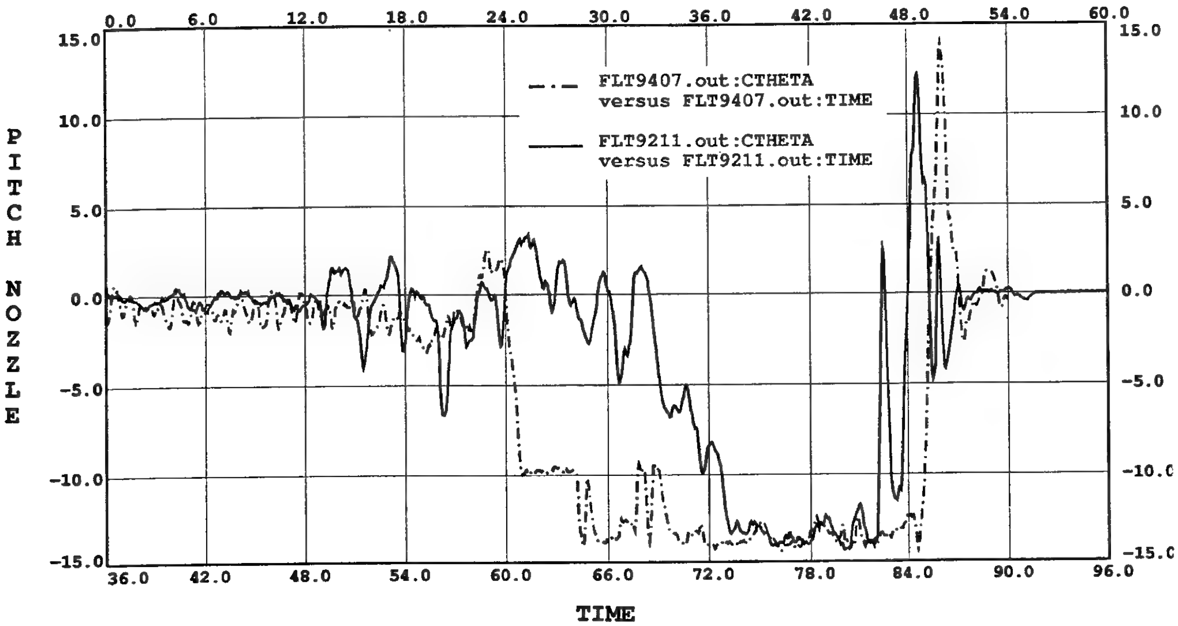


Figure 5. SAS-FLT9211 & FLT9407-Pitch Nozzle vs. Time

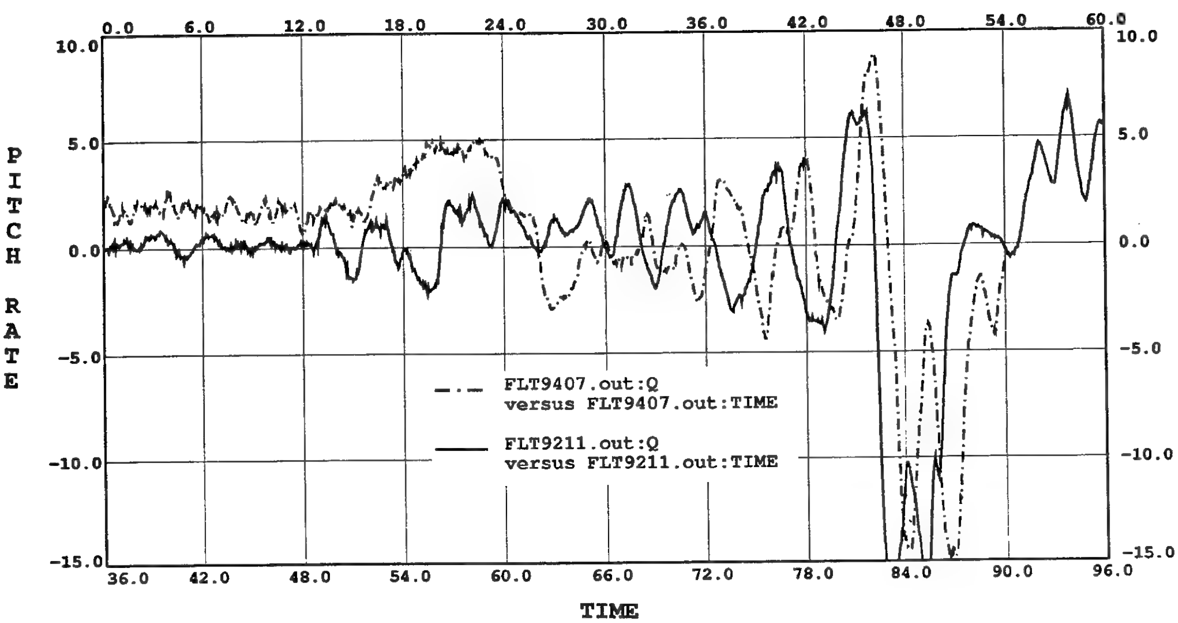


Figure 6. SAS-FLT9211 & FLT9407-Pitch Rate vs. Time

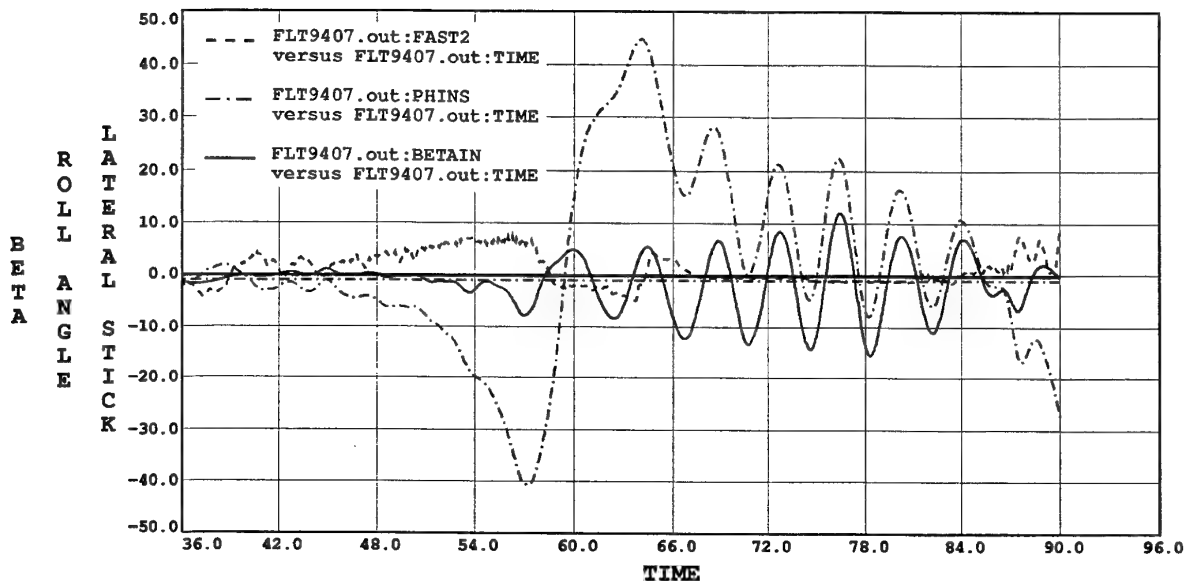


Figure 7. SAS-FLT9407(BASELINE)-Beta, Roll Angle and Lateral Stick vs. Time

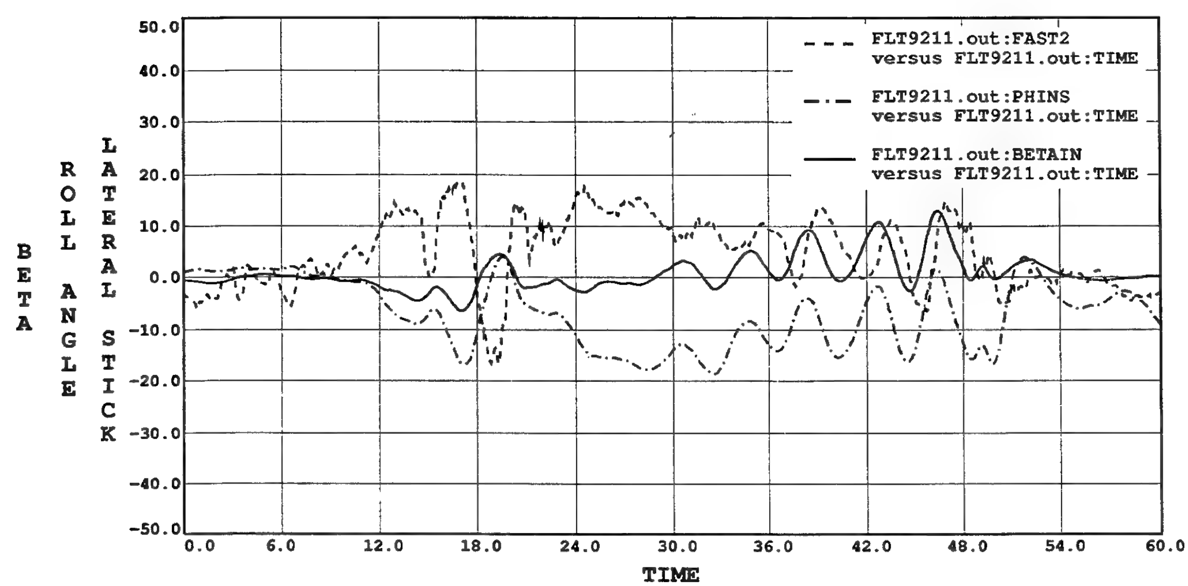


Figure 8. SAS-FLT9211(CHINE)-Beta, Roll Angle and Lateral Stick vs. Time

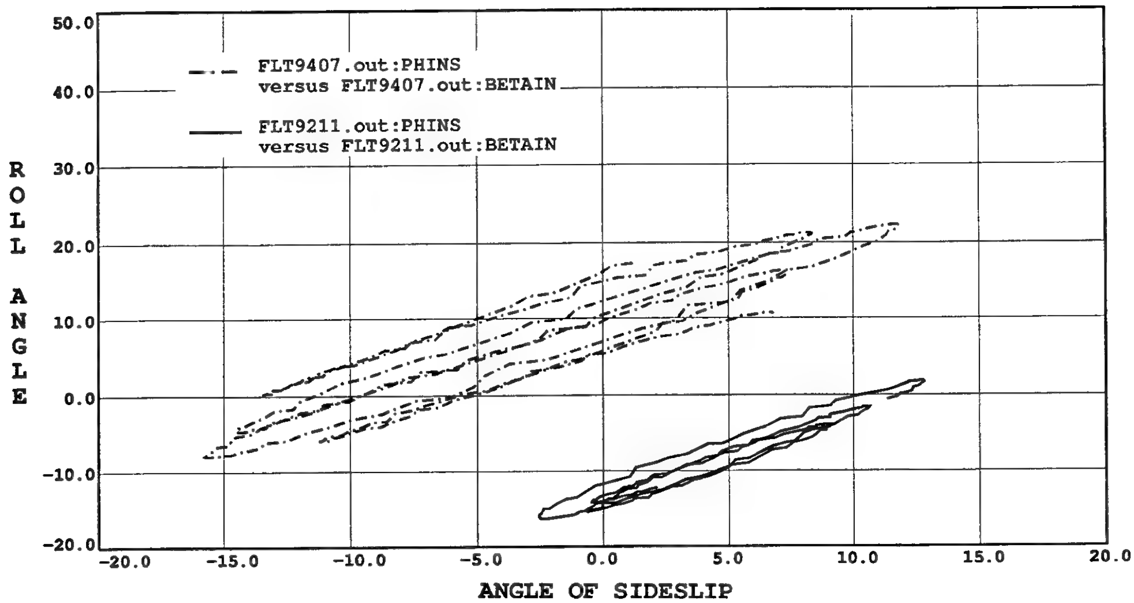


Figure 9. SAS-FLT9211(CHINE) & FLT9407(BASELINE)-Phi vs. Beta (Max Alpha)

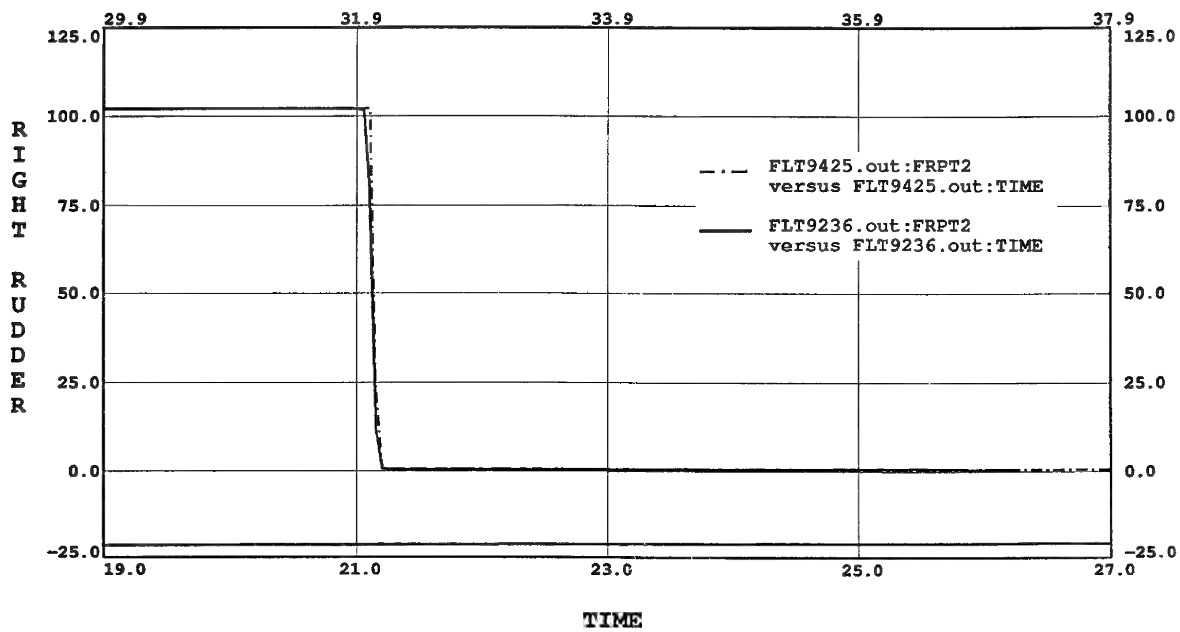


Figure 10. SSR-FLT9236 & FLT9425-Rudder vs. Time - Alpha 30

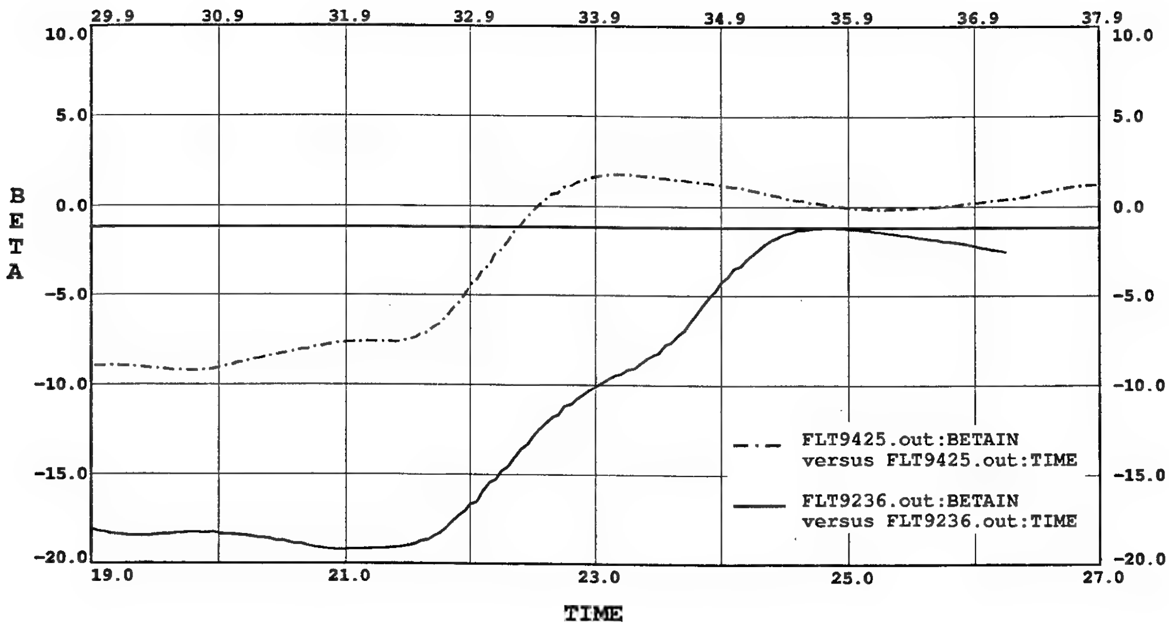


Figure 11. SSR-FLT9236 & FLT9425-Beta vs. Time - Alpha 30

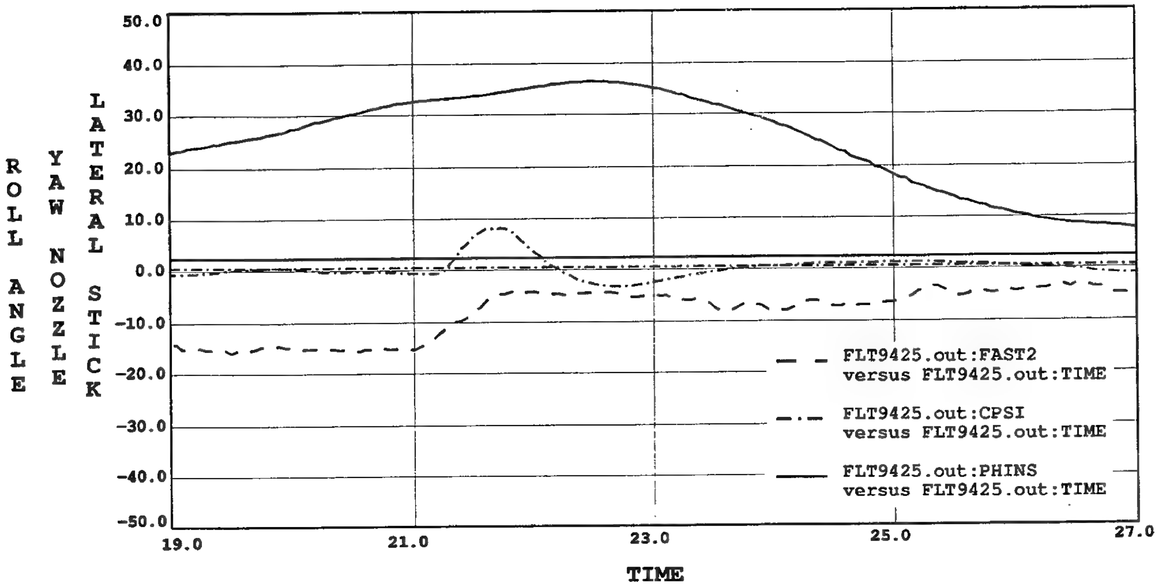


Figure 12a. SSR-FLT9425(BASELINE)-Roll Angle, Yaw Nozzle & Latstk vs. Time

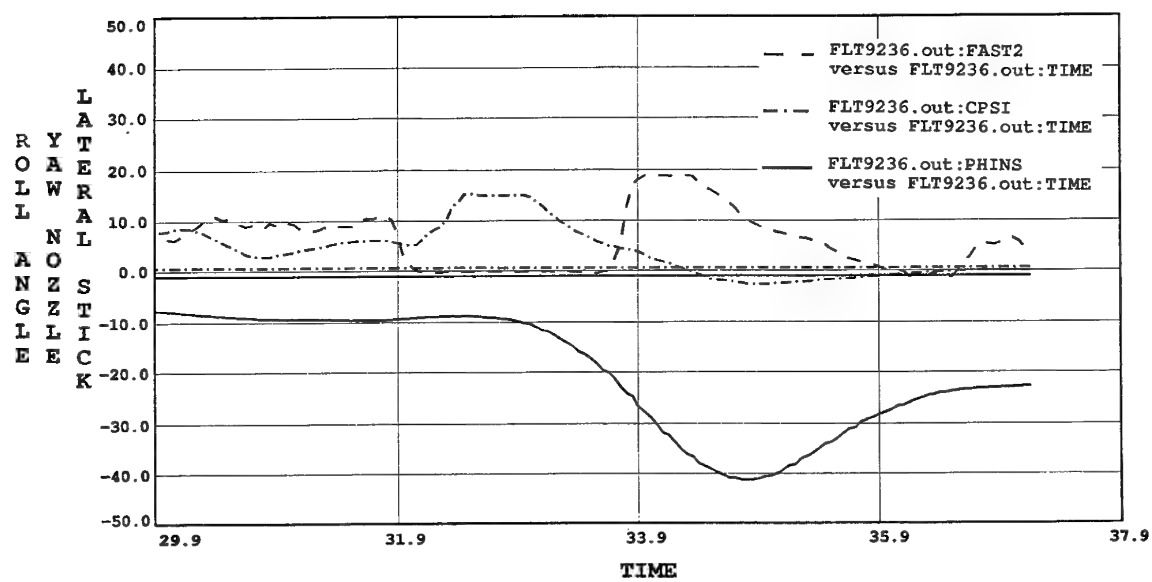


Figure 12b. SSR-FLT9236(CHINE)-Roll Angle, Yaw Nozzle & Latstk vs. Time

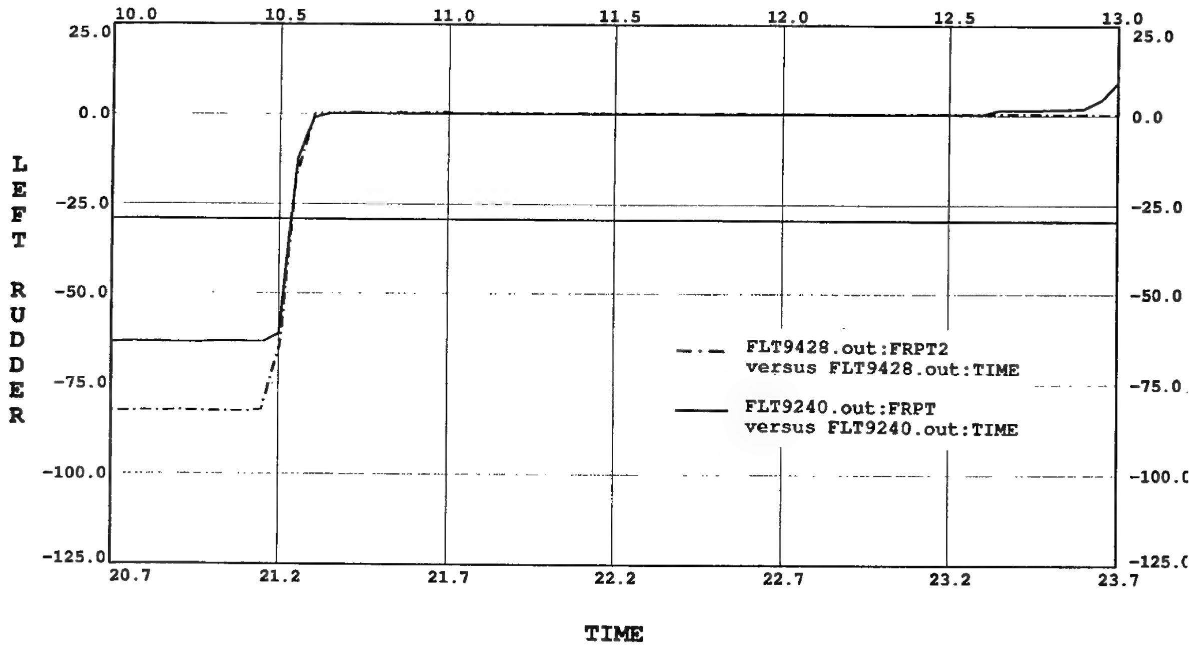


Figure 13. SSR-FLT9240 & FLT9428-Rudder vs. Time - Alpha 45

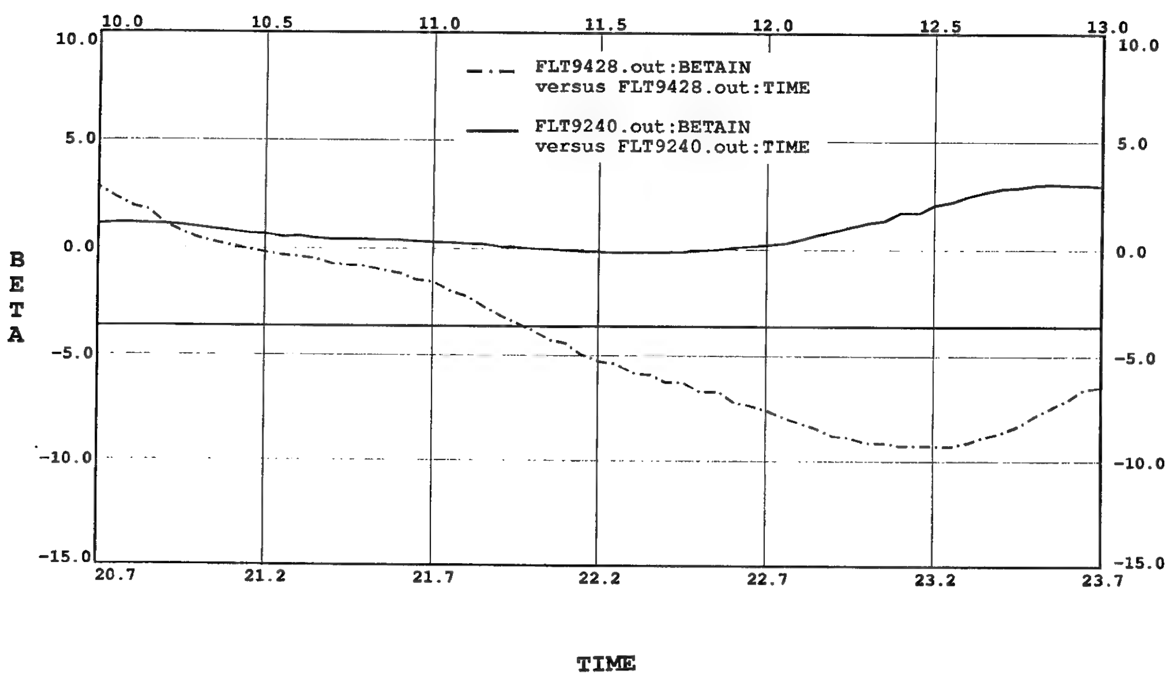


Figure 14. SSR-FLT9240 & FLT9428-Beta vs. Time - Alpha 45

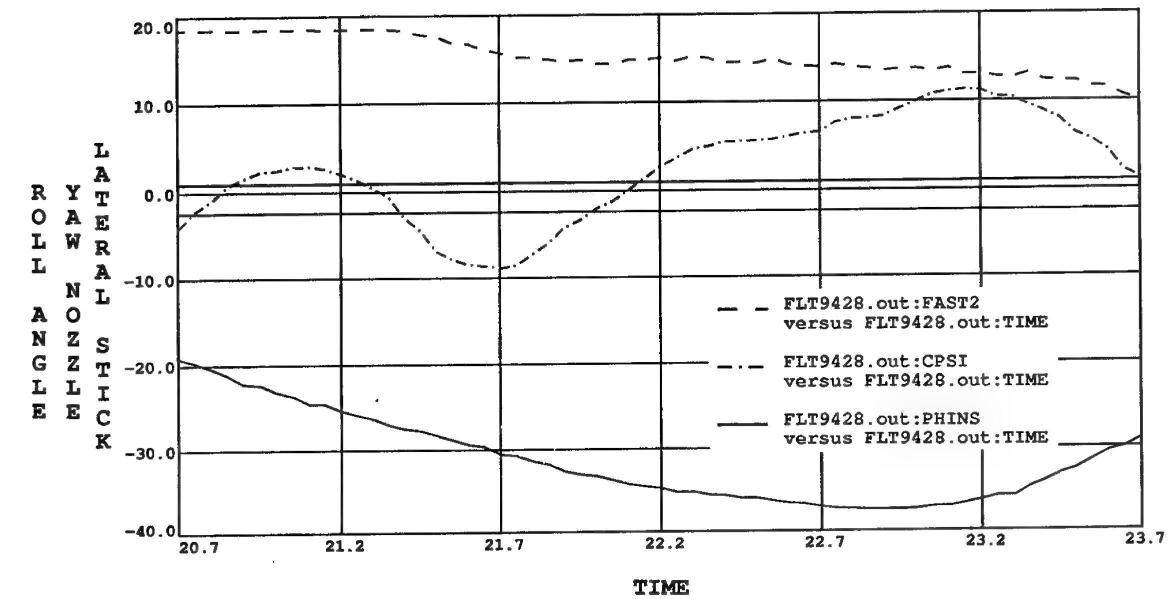


Figure 15a. SSR-FLT9428(BASELINE)-Roll Angle,Yaw Nozzle,Latstk vs. Time-45 Alpha

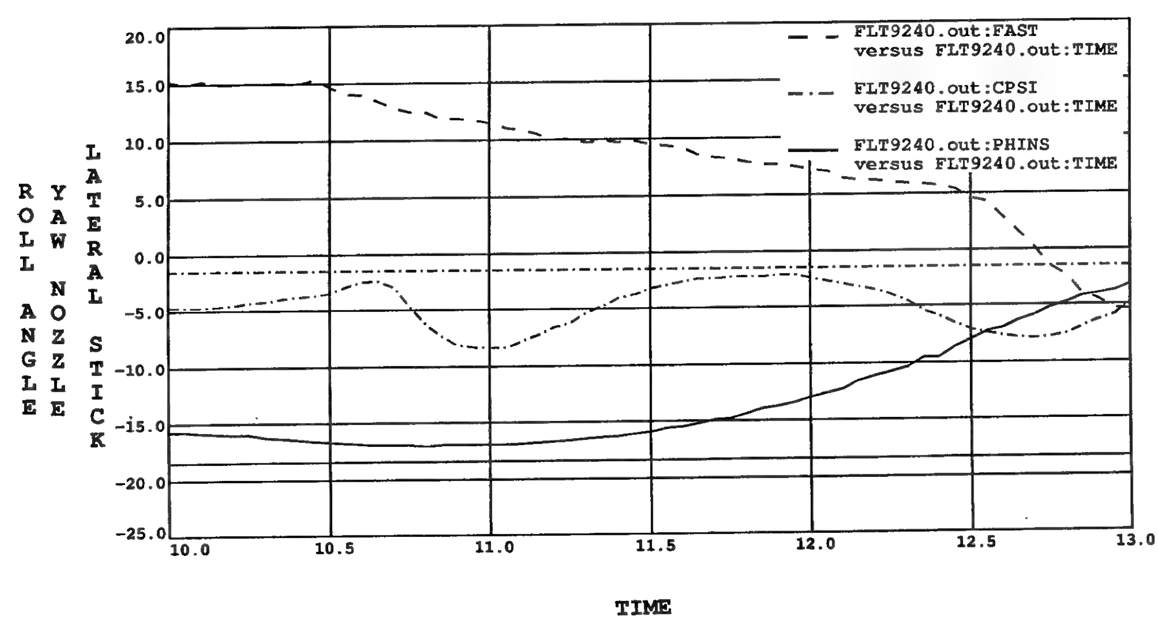


Figure 15b. SSR-FLT9240(CHINE)-Roll Angle,Yaw Nozzle,Latstk vs. Time - 45 Alpha

THE DEVELOPMENT AND USE OF IN-FLIGHT ANALYSIS AT BAE WARTON

K.M.Nanson/R.B.Ramsay
British Aerospace Defence Ltd (Military Aircraft Division)
Warton Aerodrome, Preston
Lancashire, England PR4 1AX
UNITED KINGDOM

SUMMARY

This paper describes the development and use of telemetry and in-flight analysis for flight trials at BAe Flight Test Warton. The current status of in-flight aerodynamic analysis techniques for Eurofighter is described, including those used for envelope expansion flutter testing.

The cost benefits of monitoring and analysis, and the improvement in timescale of data availability, have been demonstrated to support the extension of the in-flight analysis concept to the complete weapon system flight trials.

1 INTRODUCTION

Throughout the 1950's, 60's and 70's, telemetry has been developed progressively but slowly, initially as a safety control in spinning trials, and up to the 1970's as a means of managing sorties more efficiently. The capability to carry out in-flight analysis emerged from this and has been developed to the extent that aircraft handling and flutter characteristics can be confirmed and the aircraft envelope expanded in Real Time.

For EF2000 flight flutter certification the company has developed a computer system to analyse, confidence and display telemetered flight flutter data for comparison with predictions in near real time.

The system enables the engineer to access analysed flutter data following continuous and impulsive excitation within seconds of completion of the test point, in order to decide whether or not the aircraft can safely progress to the next test point.

The flutter ground station is used in conjunction with the aircraft excitation system which generates, within the flight control computers, predefined waveforms in the form of sinusoidal frequency sweeps and impulses which are summed into the flight control system actuation loops under cockpit control. The excitation system was developed on the Experimental Aircraft Programme (EAP) and applied to EF2000 which is presently (summer 1996) performing envelope expansion flutter testing.

2. THE HISTORICAL PERSPECTIVE

Real time data via telemetry has been available in the Warton Flight Test environment since the mid 1950's.

Prior to that time very limited data was recorded on board the aircraft via pen traces and 'Auto Observers' which photographed banks of gauges at regular intervals - the only additional data was from aircrew notes and the qualitative assessment of the pilot himself. Extraction of full engineering data from these sources was very labour intensive and time consuming. The general test philosophy was to fly as often as possible in as many conditions as possible to confirm satisfactory behaviour or identify problem areas. Problems were solved only by detailed further testing to gain understanding, trying 'fixes' and hopefully achieving acceptable behaviour. Development programes were relatively cheap to undertake, cost was not a major influence and technical innovation and performance were main drivers.

Since that time the quantity of real time data has grown from only 8 parameters in the 1950's to over 700 by the mid 1970's. However, all analysis was still carried out post flight.

By the late 1970's, computing technology and aerodynamic modelling had grown to a level to permit accurate simulation, and aspects of aircraft behaviour could be predicted and flown on a simulator before actual flight experience was available. Thus 'first level' flying qualities could be evaluated without even building an actual flying aircraft and this changed the balance of risk in the aerodynamic aspects of the flight test business from 'untested in flight' to 'confirm all right in flight'.

In parallel to this aerodynamic modelling development, aircraft telemetry had been developed from a safety control on Lightning and Jaguar spinning trials, to a sortie management facility on Tornado. Again computing technology was rapidly advancing such that telemetry data transmission rates could be significantly increased, facilitating much larger parameter quantities and/or sampling rates.

These developing situations began to influence the philosophy of flight testing in these areas from 'Test to Find the Problems' to 'Test to Confirm Satisfactory'

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

coupled with tighter sortie management. This had the potential of reducing the test flying hours and the overall amount of analysis required. If the flight data could be analysed and compared to the model/prediction during flight then potentially there were significant timescale savings to be achieved and, as long as the flight data fell within predetermined boundaries, flying could continue until a significant disparity occurred.

In the late 1970s and early 1980s technology demonstration flying programmes were underway or planned at Warton as part of the process to establish the new technologies required for the next generation of combat aircraft. One of these, the Experimental Aircraft Programme (EAP) flew in the mid 1980's and provided an excellent opportunity to develop and prove some aspects of what became termed Real Time Analysis (RTA).

The aerodynamic modelling of EAP was necessarily of a high fidelity, due to its unstable configuration, and the simulator was an essential element of the flight clearance process. BAe saw this as an ideal opportunity to further our RTA ideas. The decision was therefore made that the Stability and Control and Loads flying would be carried out using RTA to a strict clearance procedure which permitted envelope expansion to continue in real-time as long as measured responses matched prediction and the loads remained acceptable.

Fig 1 summarises the developing capability of telemetry at BAe Warton.

3. EF2000 ENVELOPE EXPANSION PROCEDURE

During development envelope expansion flying the flutter and aerodynamic handling testing is integrated according to the following rules:

i) all flutter testing is at "1g" trimmed condition

ii) a set of handling manoeuvres is carried out at least sufficient to support the flutter testing

iii) handling testing must lag the flutter testing by a defined minimum airspeed margin

iv) flutter testing cannot lead the handling testing by more than a defined maximum Mach number margin

v) during handling and flutter testing, the airframe dynamic loads are continually monitored.

The envelope expansion progresses in airspeed and Mach number to produce sufficient evidence for a clearance for that particular aircraft. This will then release other development aircraft, with the same design standard, to expand their flying programme in terms of airspeed and Mach number limits.

4. RTA FOR EF2000 AERODYNAMIC ENVELOPE EXPANSION

The invaluable experience gained on EAP was used to improve the Flight Test Data Acquisition Ground Station resulting in the arrangements shown in Fig 2 being operational toward the end of 1993 . This Ground Station arrangement consists of an APTEC 10C-24 data highway linking a Vax cluster of computers and SUNSPARC Workstations. In addition, because the aerodynamic models were hosted on the Warton Site Mainframe Computer, the Flight Test Vax Computers were linked to the Aerodynamics Computers via a fibre optic computer link.

Two Telemetry Rooms and a Dynamics Analysis Room now exist, with two separate 'front ends' enabling simultaneous parallel or independent use as required by the test programme. In addition, further RTA workstations are installed in the main Flight Test office to increase throughput whilst maintaining sufficient sortie management and pilot assistance in the Telemetry Rooms themselves. This was put to the test in April 1994 with the first flight at Warton of EF2000, and is currently in use supporting EF2000, Tornado and Hawk flight trials.

The tools and techniques currently in place (1996) are shown in Fig 3 and are described below for:

i) general aerodynamics, loads, FCS, air data, and

ii) flutter.

4.1 General Aerodynamics, Loads, FCS, Air Data

- Manoeuvre Identification and Validation: EAP experience indicated that close control of input data was required to ensure effective RTA. A two step process is now being used; manoeuvres are identified by capturing timeslices derived from scrolling displays of primary parameters, as shown in Fig 4. Minimum/ maximum/start/average single point values during the timeslice are then stored to give an instant summary listing as shown in Fig 5. The manoeuvre is validated by comparing it with control input and flight condition acceptance criteria using predefined overlays and tolerances on a similar scrolling display (Fig 6). If the test point passes these criteria it is immediately released for RTA, as described below.

- Fast Fourier Transform (FFT): The FFT technique is used to analyse the combined aerodynamic and flight control system stability characteristics using excitation generated by automatic frequency sweeps of the primary Flight Control System (FCS) actuators. Phase and gain plots are compared with pre-flight predictions with 'worst case' tolerances applied as shown in Fig 7. Provided the

flight data lies within acceptable boundaries, the envelope expansion can continue. The analysis is carried out on a dedicated Hewlett Packard computer located between the 2 telemetry rooms, and analysed data is available within approximately 60 seconds of the end of each frequency sweep.

- Cross-Plots: Flight data is cross-plotted in real time using the workstation display technology, with predicted lines and/or limits overlayed. Fig 8 shows a typical plot for maximum roll rates during a rapid roll entered at 2g on EF2000 with an early FCS standard. The upper and lower predicted boundaries in Fig 8 were determined using 4 tolerance cases involving aircraft mass and the `yawing moment due to roll rate` (Cnp) aerodynamic derivative i.e.

high and low mass using Cnp upper tolerance
high and low mass using Cnp lower tolerance.

On EAP the cross- plotting was mechanical with predictions hand drawn on the graph paper pre-flight. Thus the technology is far more convenient and flexible whilst the methodology remains unchanged and entirely satisfactory.

- Flight Mechanics Reprediction: Flight responses are compared with modelled responses using the actual control input and flight conditions. Pre-identified start conditions are needed to run the model and when the model 'sees' these conditions, the Test Conductor is informed automatically via his workstation display. He then asks the pilot to commence the required manoeuvre. Selected tolerance cases are run to give an 'acceptance' band of responses and software assesses whether the flight data lies within these bands. The Flight Test engineer then assesses the comparison and decides whether the response is acceptable. The model is hosted in the Flight Test Workstation, and results are available less than 2 minutes post manoeuvre.

- Derivative Extraction: EF2000 aerodynamic derivatives are determined by aerodynamics data set specialists via the fibre optic link, using the `Equation Error` method which is the first time this technique has been used to routinely validate the aerodynamic model of an aircraft flight tested at BAe Warton. This technique is considered to have a number of advantages over the `Output Error` method previously used at Warton, particularly for analysing highly non-linear aerodynamic functions. Analysis can commence as soon as the manoeuvre is carried out and results can be available for post-flight de-brief if required.

- Loads Calculation: Computation of loads from measured aircraft responses is available by running the Loads model on a mainframe computer via the fibre optic link. This method allows loads to be compared with allowable envelopes within a few seconds of the test manoeuvres, and is being used throughout the envelope expansion phase of EF2000.

- Air Data Disparities: Disparities between different air data sources are automatically checked in real time and warnings displayed on parameter tabulations if significant disparities are identified. Further analysis can then be carried out. Flight data is also cross- plotted in real time on SUNSPARC workstations. Comparison with disparity boundaries or limits is carried out by selecting relevant menus for overlaying the flight data. Data trends are assessed to ensure accuracies remain within the levels assumed for clearance and to anticipate exceedance of monitored threshold levels. Thus planned degradations of aircraft systems can be avoided, enhancing trials safety and efficiency.

- Flight Control System (FCS) Status: The FCS status for EF2000 is displayed on a work station during pre-flight, flight, and post-flight phases. The displays include:

a) FCS status e.g. FCS mode, cockpit failure warnings, cockpit switch and pushbutton selections

b) Sub-systems status e.g. Inertial Measurement Unit (IMU), Air Data Computers (ADC), Air Data Transducers (ADT), Air Intake Pressure Transducers (AIPT)

c) Failure Identification Tables (FIT)

d) Lists of parameter values for data analysis

e) A table for the creation of an FCS flight report, which is automatically updated whenever the values of specified parameters change to a new constant value.

4.2 Flutter

Flutter testing and analysis is fundamental to the progress of envelope expansion testing. Therefore the real time flight flutter system and analysis being performed is described in some detail below.

The second development Eurofighter aircraft (DA2) based at BAe Warton is the designated aircraft for flutter envelope expansion in the basic Air-to-Air configuration.

DA2 envelope expansion testing commenced on the 17th May 1995, which was the tenth flight of the aircraft and the first flight with the Phase 1 upgrade Flight Control System (FCS). To date (summer 1996) a total of 104 flights (or 91 flight hours) have been completed of which 67 flights have been dedicated to flutter testing.

Figure 9 shows the overall rate of flying and the number of flights dedicated to flutter during the envelope expansion phase of flying. The flutter testing to date, corresponds to 78% of the flutter programme in the baseline configuration. General aircraft handling is integrated into the flutter programme, sufficient to allow progress of the envelope expansion , and 17 flights have been dedicated to handling.

Figure 10 shows the rate of flutter testing in terms of completed test points.

Figure 11 summarises the flutter envelope expansion status to date in terms of Mach number and airspeed.

A computer system has been developed for EF2000 to analyse, confidence and display telemetered flight flutter data for comparison with predictions in near real time. The system enables the engineer to access analysed flutter data following continuous and impulsive excitation within seconds of completion of the test point, in order to decide whether or not the aircraft can safely progress to the next test point.

The results in the form of plots of frequency and damping against airspeed (or Mach number) can be compared directly with predictions matched to ground resonance testing.

Telemetered Pulse Code Modulation (PCM) flutter data is received, calibrated and elaborated by the front end computer. The data is then passed to the APTEC input/output computer which acts as a database for peripheral display and analysis devices. The flutter station is hosted by a MicroVax 3500 which provides a user interface for control of the transputer system.

Figure 12 shows schematically the flutter ground station system and the interface with Flight Test. The system comprises of a transputer system, supporting three monitors, and controlled by a MicroVax 3500.

The analysis module accepts and analyses telemetered PCM data for twenty channels sampled at 512 samples per second from the surface being excited (continuous or impulse excitation). The telemetered FTI requirements for analysis of a particular surface is pilot selectable via a central control unit (CCU).

The analysis screen displays data for four channels at a time showing the impulse response, power spectral density, Argand plot and the frequencies and damping of the four extracted modes.

Continuous display of selected air data (e.g. altitude, Mach number, airspeed) are available in order to check the test point conditions against those scheduled.

The auto data monitor and trend display is used for displaying the results of the analysis along with the results from previous test points and theoretical predictions. The displays comprise of four graphs showing frequency and damping against airspeed for different levels of confidencing. In addition to the analysis system, aircraft flight test instrumentation (FTI) time histories are continuously monitored on pen playouts.

Details of the computer system are given in Reference 1.

4.2.1 Flutter Excitation System and Instrumentation

The aircraft standard for flutter testing will include specific stores and fuel states which are considered flutter critical.

For EF2000, use is made of the in-flight structural mode excitation system designed to excite the foreplane, wing trailing edge flaperons and rudder. The excitation is by injecting signals into the primary control actuators, using profiled frequency sweeps and impulse input, to establish measured structural frequency and damping trends in the critical flutter modes and to compare with the theoretical predictions. Details of the structural mode excitation system are given in Reference 2.

The instrumentation used to record structural vibration in the range of interest are piezo-electric accelerometer transducers with a power unit amplifier. The instrumentation requirements are defined by the flutter specialist following aircraft simulated response modelling using the excitation system inputs.

Figure 13 shows the positioning of the instrumentation on EF2000 to measure structural responses in the fundamental modes of the wing, foreplane and fin. In addition to accelerometer responses the FCS excitation primary actuator input demands are recorded in order to perform transfer function analysis.

4.2.2 Flight Flutter Testing

The Flight envelope is expanded by carrying out a Mach number/airspeed survey to obtain flutter measurements. The survey initially concentrates on areas of the flight envelope with predicted high flutter stability. This clears the areas of the envelope for handling and other trials, whilst the flutter engineer investigates more critical areas of the flight envelope.

In general, test points are flown once and the airspeed/Mach number increment is chosen based on the proximity to regions of low predicted stability.

Figure 11 shows a plot of the flutter test points superimposed on the flight envelope. Progression is normally in increments of 50 knots, but is reduced to 25 knots where a particular surface requires investigation.

Where observed flight responses are as, or better than, predicted by pre-flight calculation, no restriction to progressing to the next test point will apply. Where

differences exist, a detailed assessment of the implications may be needed.

4.2.2.1 Data Acquisition and Analysis

During the initial flying a number of problems were experienced with the data acquisition system, data reception, spikes, drop-outs and pen playout delays due to PCM group changes. In order to improve the reception the location of the antenna on the wing tip pod was re-positioned, however problems still exist with the aircraft close to the airfield and also care must be taken when using chase aircraft in the close proximity of the test aircraft.

In order to deal with spikes and drop-outs the data is continuously monitored against a tolerance level and, for spikes, linearly interpolates between the good data. In the case of drop-outs due to data loss the last good data is taken and padded out for the loss of data. Where data loss is identified during the flutter excitation run, particularly in the region of a resonance, the pilot will be requested to cancel the input and re-position the aircraft.

No major problems have been encountered during flutter testing with data quality, apart from some initial tests which did not "pad-out" the data from drop-outs for analysis and caused time lag problems with transfer function analysis. During flutter testing at a given test point, pilot selected CCU changes of PCM data had significant delays (2-3 minutes) before being displayed on the pen banks. The problem was due to the density of data being transmitted and a function of the number of telemetry personnel making menu changes at that time. This problem was overcome by minimising menu changes and partitioning only the data required for flutter analysis.

4.2.2.2 Typical Test Results and Comments

Figures 14 and 15 show the frequency and damping measurements with airspeed at M=0.8 for continuous symmetric foreplane excitation. Transfer function analysis has been performed on the foreplane acceleration responses using the FCS excitation signal as the input.

The torsion and yaw mode frequency trends with airspeed (Figure 14), reduce significantly with increase in actuator input demand amplitude, above 350 KEAS. This force/frequency effect is similar to that seen during the foreplane GRT. In addition to the force/frequency effect the increase in frequency compared to prediction for all three modes of vibration is due to steady air loading effects. Examination of the foreplane static bending test results indicate a 15% increase in stiffness when loads above 20% of the ultimate load are applied.

In the case of the damping trends with airspeed (Figure 15), the bending and torsion damping trends agree with prediction. The yaw mode damping reduces with increase in airspeed, corresponding to the increase in excitation level. It should be noted that the predictions do not include structural damping but do include actuator damping. The scatter in the foreplane bending damping is due to the individual port and starboard foreplane dampings, which are a function of the foreplane build tolerances.

Figures 16 and 17 show the frequency and damping measurements with airspeed at M=0.8 for continuous symmetric wing excitation using full trailing edge flaps. Two methods of analysis were used on these measurements, transfer function analysis and autocorrelation analysis, and it was found autocorrelation gave a better match to predictions. Checks show that there is constant power throughout the frequency range of the wing sweeps, as required for valid autocorrelation analysis.

From the 2-30 HZ wing sweep the symmetric wing bending and torsion and AIM-9L missile stub pylon frequencies have been identified and agree closely with prediction (Figure 16). The actuator input demand amplitude for all airspeeds is restricted to 1/3 full amplitude due to the dynamic loading restrictions on the outer wing. As a result the wing responses are significantly lower (5-8g peak) compared to the foreplane responses. However the data quality is very good, even in the transonic Mach number range, and this results in high confidence frequency and damping data.

In the case of damping trends with airspeed (Figure 17) the wing bending trend shows good agreement with prediction although there is some scatter at low airspeed due to the low wing response levels. It should be noted that the predictions do not include structural damping. The wing torsion damping trend, in general, agrees with prediction. The large scatter in the torsion dampings is mainly due to the differences in the port and starboard wing dampings, due to carrying asymmetric wing tip pods, rather than poor quality flight data.

It was also concluded from the measurements that the influence of the flight control system had no effect, when compared to the open loop predictions.

5. FUTURE DEVELOPMENT

The above describes the current implementation of RTA which is in use now for EF2000 aerodynamic envelope expansion trials. The system is fully operational and its performance has completely justified the confidence and investment decisions taken at the outset some 10 years ago.

The focus of development has now turned to the implementation of RTA to avionic and weapon system flight trials and the aspects being addressed are outlined in the following section.

Traditionally telemetry has not been used at Warton for avionic or weapon system flight trials for a number of reasons eg. security restrictions of unencrypted telemetry data, the large quantity of data, the wide range of data sources (some off aircraft) required for effective analysis, and cockpit display recording technology. However, the advancement of technology in some critical areas is now such that the majority of the previous instrumentation issues can be overcome at reasonable expense thus enabling the philosophy to be reviewed and updated. This was considered back in the late 1980's and led to the decision to equip all the test aircraft on the next major project, EF2000, with data and video encrypted telemetry. This was the first step in a much larger process to move towards more effective and productive avionic and weapon system flight trials.

Other considerations also drove the desire to achieve in-flight monitoring and analysis for this type of trial such as:-

- The relatively high pilot workload in modern single seat multi-role aircraft: an acceptable level is achieved in the operational product by high automation of the systems and fusion of the sensor data. However, during development this is not the case, and to maintain test effectiveness with reasonable pilot workload it is highly desirable to put the engineers 'in the cockpit' via comprehensive telemetry.

- The change in philosophy of ground based testing towards extensive modelling and rig trials to achieve highly developed systems prior to actual flight: the concept of flight testing could therefore change from 'Test to Find the Problems' to 'Test to Confirm Satisfactory' - as had already been achieved for aerodynamic aspects as previously described.

The scenarios outlined above have resulted in a Flight Test vision to achieve avionic and weapons system RTA by 1998. To achieve this aim a number of areas are being addressed to establish the required facilities as outlined below:-

- The provision of high quality reference data in real time: this is required as input data to avionic and weapon system models so that model output data can be compared with aircraft data in real time. Instrumented Range data is to be supplied in real time into the Telemetry Rooms as well as GPS data from both the test and the target aircraft.

- The provision of data in real time for situation awareness and sortie management in the Telemetry Room. This will require the integration of the reference data noted above with databus and video data to provide information such as cockpit selections, sensor coverage, absolute and relative aircraft/target positions and pilot displays together with a view of the outside world.

To achieve this capability a great deal of work has already been undertaken and will continue in the coming years. The increase in the effectiveness of flight testing that we expect to achieve is a significant step forward from that previously demonstrated and our confidence is such that we are assuming it to be the baseline standard for projects beyond EF2000.

6. CONCLUSIONS

The development of in-flight techniques at Warton has enabled the original concept to be successfully used for aerodynamic flight trials since the mid 1980s and a measurable increase in effectiveness has been demonstrated. The continuing improvements in technology has now enabled this concept to be realistically considered for avionic and weapons system flight trials in the future and current development is focussed on these areas.

Although the flutter clearance approach involves increased manpower effort prior to flight, the overall method used on EF2000 has shown to be directly cost effective by reducing the number of flights required compared to previous projects.

A second major benefit to the company is that of compressed time scales for flight envelope expansion on EF2000 compared to previous projects. This is highly desirable given the tight time scales for the project as a whole.

The methods and procedures used on EF2000 for flutter qualification and certification have evolved over a number of years and are a result of close liaison between Departments and with National authorities and the experience gained in understanding the complex flutter mechanisms such as occur on Tornado, EAP and EF2000.

The approach has proved safe and effective in obtaining optimised clearances where flutters within the target flight envelope have been identified.

7. ACKNOWLEDGEMENTS

This work has been carried out with the support of the Procurement Executive, Ministry of Defence.

The authors wish to acknowledge all members of Warton Flight Test and Aerodynamics Departments both for their contributions to this paper and particularly to the work

that has been and is to be undertaken to bring the in-flight analysis concept into a full reality.

REFERENCES

[1] R.B.Ramsay. Flight Flutter Testing of Combat Aircraft.
AGARD-CP-566, Paper No.18, 1995.

[2] R.B.Ramsay. In-Flight Structural Mode Excitation System for Flutter Testing.
AGARD-CP-519, Paper No.15, 1992.

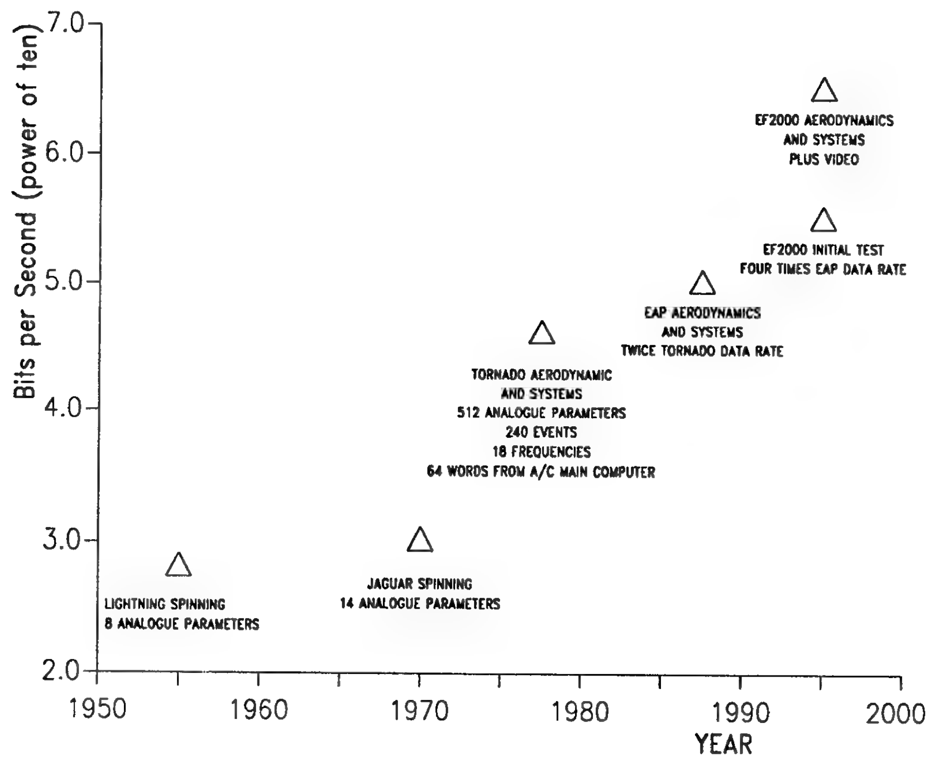


FIGURE 1: HISTORY OF TELEMETRY DEVELOPMENT AT WARTON

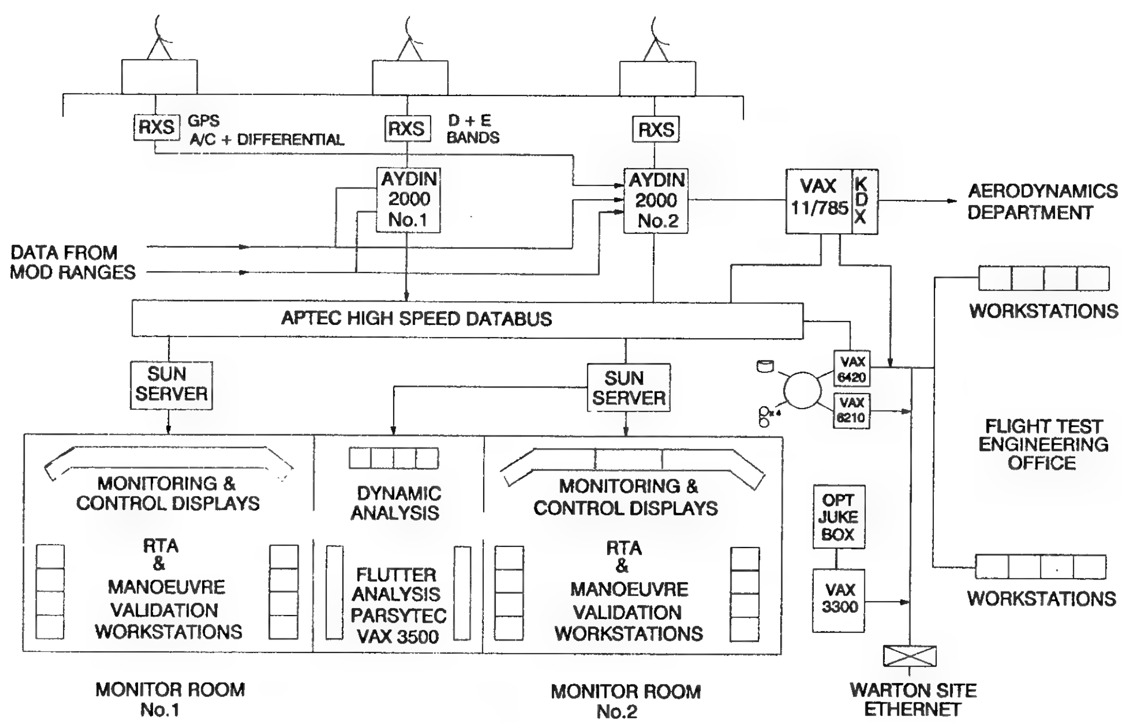


FIGURE 2: CURRENT GROUND STATION AT WARTON

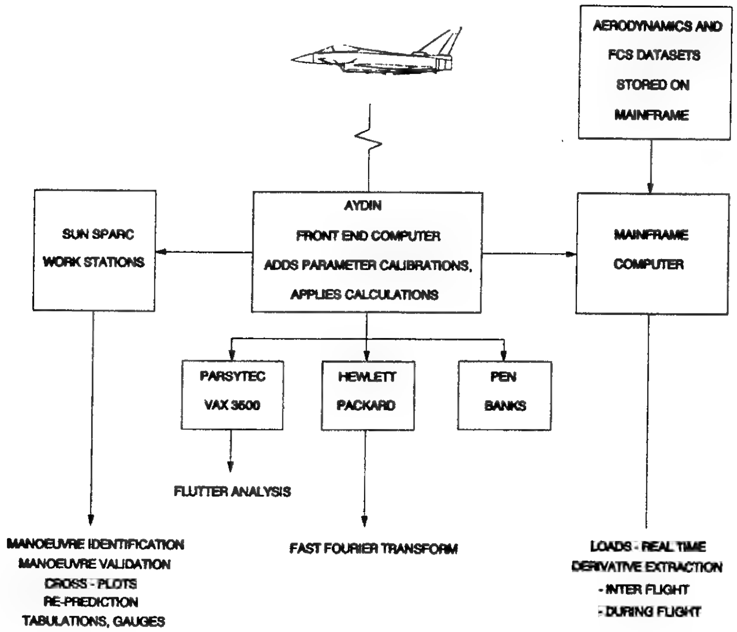


FIGURE 3: REAL TIME ANALYSIS - EF2000

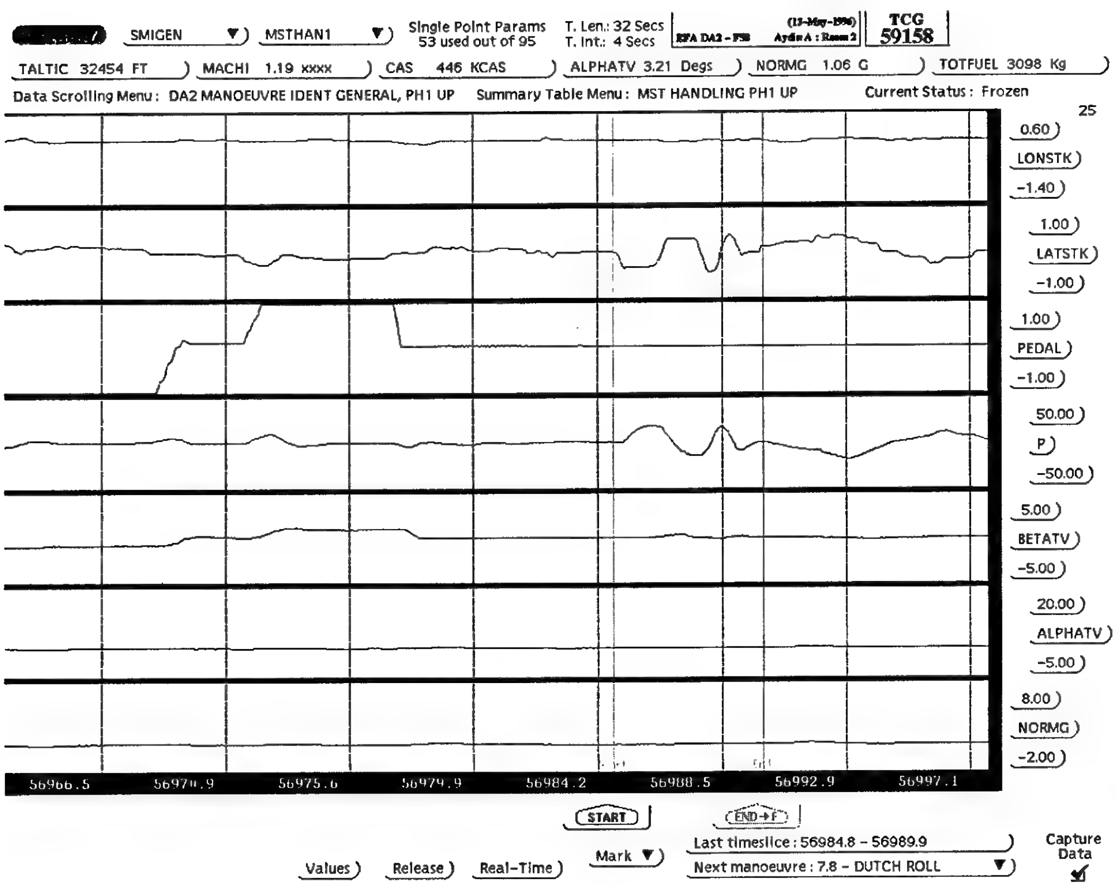


FIGURE 4: MANOEUVRE IDENTIFICATION DISPLAY

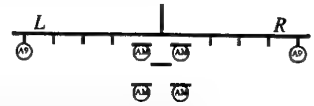
Pilots : P Hopkins

OAT : 1 C
QFE : 1021
Wind To : 070/10kt
Wind Ld : 060/12kt

Reference Number : ZH588
Loadsheet Number : 5/1/4
Add. :

Print Date : (14-Jun-1996)

Takeoff Configuration (Rear view) :-



Aircraft standard :-
FCS PHASE 1 UPGRADE

Page 1a **Single Point Values**

Number	Manoeuvre	Timeslice	Comment	Menu name	TALTI Feet AVG	TMN Mn AVG	DAS Knts AVG	DAS Knts MAX	DAS Knts MIN	ABRAKES Deg SRT	LMGDOWN BITS AVG	ALPHATV Degs SRT
				Spike Supp.	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
1.1	DATA START	51399.0 - 51404.0	PFC PASSED	MSTHAN3	-225	0.04	28.4	62.1	0.00	-5.31	2.00	40.9
1.2	ALPHA/BETA VANE MVMT	51400.0 - 51426.0		MSTHAN3	-225	0.01	3.73	12.7	0.00	-5.52	2.00	27.4
1.3	ENGINE START	51465.1 - 51498.4	Left	MSTHAN3	-227	0.00	2.09	8.55	0.00	-5.21	2.00	40.9
1.4	ENGINE START	51531.9 - 51567.8	Right	MSTHAN3	-226	0.00	2.22	7.96	0.00	-5.48	2.00	40.9
1.5	AMC	51819.8 - 51921.9	PASSED	MSTHAN3	-230	0.01	3.53	9.05	0.00	-5.63	2.00	40.9
1.6	FRS ENTRY	51928.6 - 51933.5		MSTHAN3	-231	0.01	3.97	7.72	0.00	-5.31	2.00	40.9
2.2	FBI GND CHECK	52138.4 - 52157.5	Case 01 (ICO'd)	MSTHAN3	-230	0.01	3.36	7.74	0.00	-5.67	2.00	40.9
3.1	GOVERNOR CHECK	52476.4 - 52524.0		MSTHAN3	-235	0.01	9.34	16.7	0.00	-5.78	2.00	-3.23
4.1	ENGINE PLACARD CHECKS	52530.0 - 52558.4		MSTHAN3	-236	0.02	10.5	15.5	4.85	-5.84	2.00	0.18
6.1	TAKE OFF	52602.7 - 52633.6	Rwy 08	MSTHAN3	-165	0.18	116	268	6.07	-5.80	1.66	2.47
13.2	FBI TEST CASE	53155.6 - 53218.8	Case 18	MSTHAN3	23671	1.39	575	581	570	-5.58	0.00	2.04
13.3	FBI TEST CASE	53234.1 - 53240.3	Case 39	MSTHAN3	23554	1.40	580	582	577	-5.65	0.00	2.09
13.4	FBI TEST CASE	53259.2 - 53322.3	Case 21	MSTHAN3	23647	1.38	574	583	562	-5.51	0.00	2.04
9.2	PITCH 3211	53735.0 - 53745.2		MSTHAN3	20095	1.09	505	509	502	-5.29	0.00	2.18
9.2a	PITCH 3211	53759.6 - 53767.9		MSTHAN3	20170	1.09	506	507	505	-5.61	0.00	2.17
9.3	DUTCH ROLL	53770.0 - 53775.0		MSTHAN3	20193	1.09	506	506	505	-5.31	0.00	2.26
9.3a	DUTCH ROLL	53778.0 - 53783.7		MSTHAN3	20118	1.09	507	507	506	-5.26	0.00	2.24
9.4	PARTIAL ROLL	53793.8 - 53801.9	Left	MSTHAN3	19902	1.09	509	511	508	-5.62	0.00	2.26
9.4a	PARTIAL ROLL	53806.4 - 53814.6	Right	MSTHAN3	19344	1.09	514	516	511	-5.39	0.00	2.06
9.6	SHSS	53816.4 - 53832.1	Left	MSTHAN3	18967	1.06	508	512	507	-5.27	0.00	2.11
9.6a	SHSS	53832.4 - 53845.9	Right	MSTHAN3	18981	1.07	509	510	508	-5.65	0.00	2.11
9.5	LATERAL 3211	53846.0 - 53855.3		MSTHAN3	19097	1.07	511	512	510	-5.36	0.00	2.07
9.7	ROLLER COASTER	53860.8 - 53877.1		MSTHAN3	19217	1.06	506	509	502	-5.28	0.00	2.15
9.8	PUSH OVER	53877.8 - 53890.9		MSTHAN3	18808	1.04	502	508	498	-5.59	0.00	2.26
901	TOUCH AND GO	54356.9 - 54436.6		MSTHAN3	143	0.25	167	211	146	-5.34	1.64	11.9
14.0	LANDING	54472.1 - 54556.8	Rwy 08	MSTHAN3	38.4	0.21	141	183	49.5	-5.46	2.00	9.68
15.0	REPEAT PFC	55029.6 - 55083.1	FAILED	MSTHAN3	-229	0.01	3.97	9.10	0.00	-5.32	2.00	40.9
15.1	ENGINE STOP	55120.8 - 55131.6		MSTHAN3	-228	0.01	3.78	8.69	0.00	-5.30	2.00	40.9

UP TO 50 COLUMNS OF FLIGHT DATA

FIGURE 5: MANOEUVRE SUMMARY TABLE

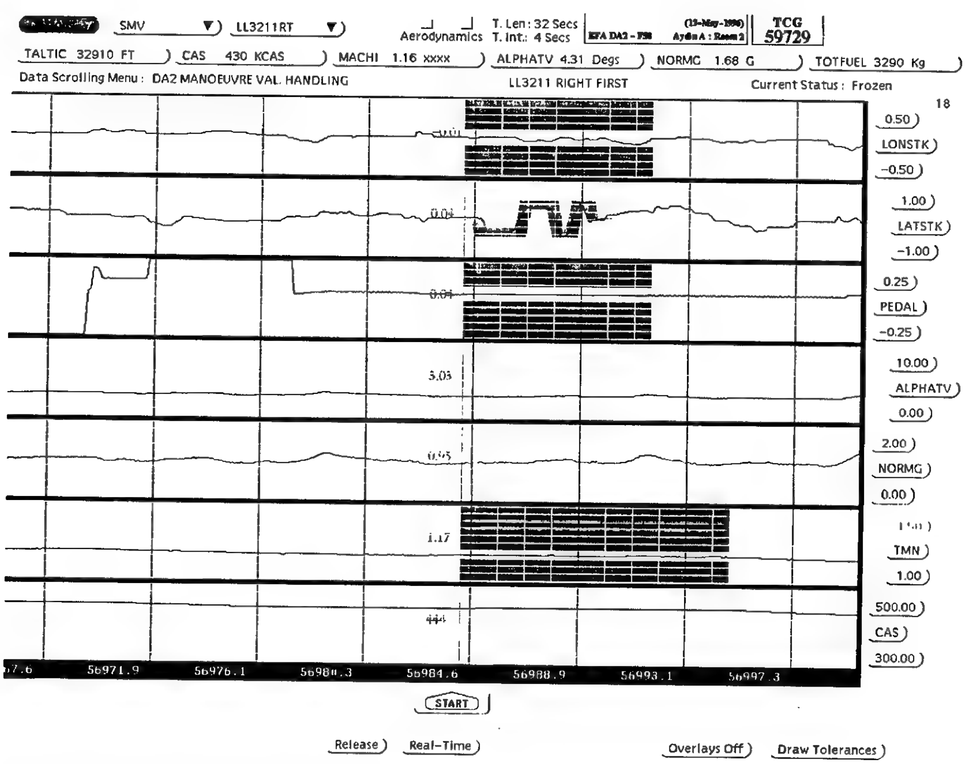


FIGURE 6: MANOEUVRE VALIDATION DISPLAY

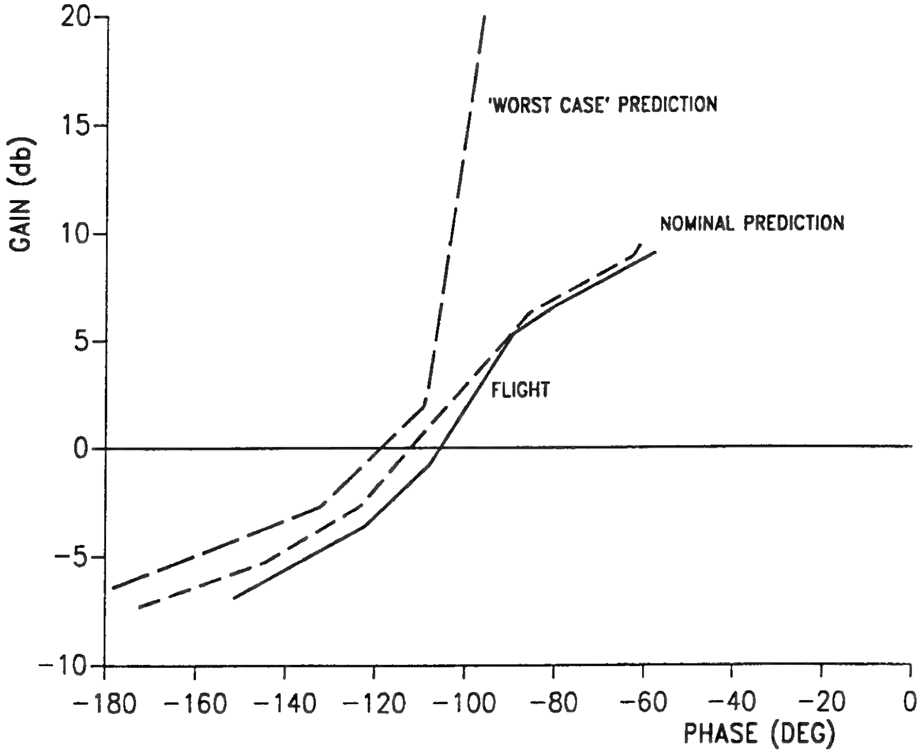


FIGURE 7: PHASE AND GAIN FROM FFT ANALYSIS

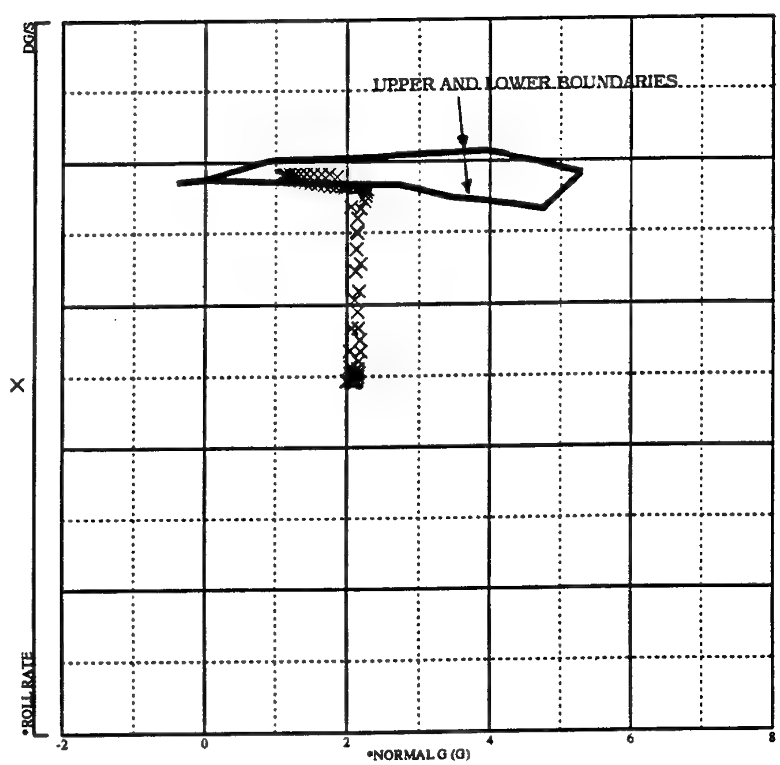


FIGURE 8: CROSS-PLOT AND BOUNDARY DISPLAY

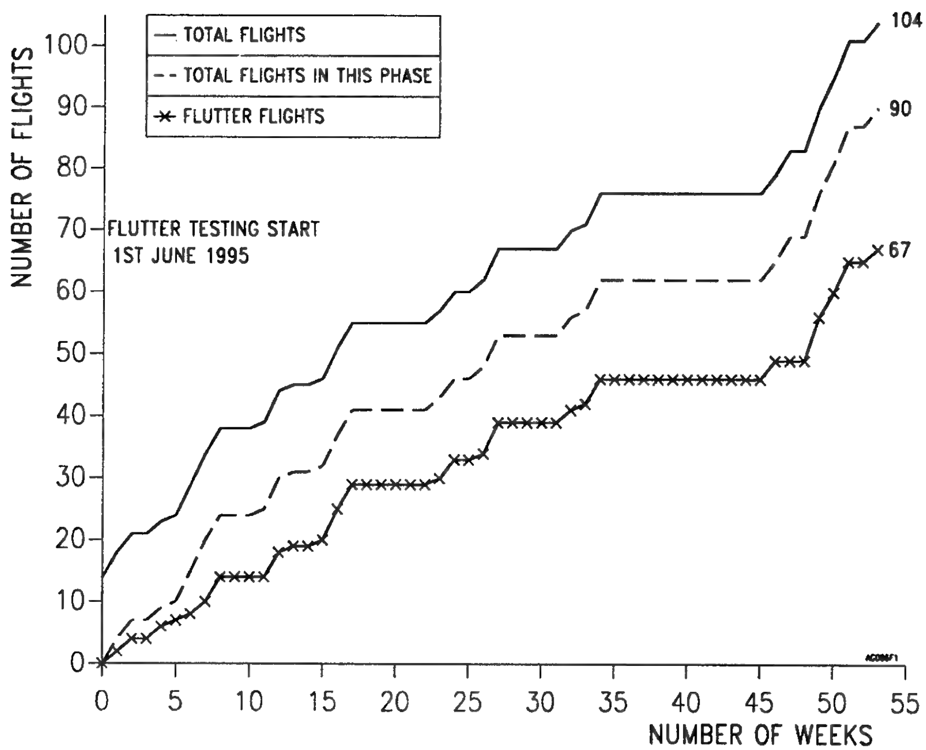


FIGURE 9: DA2 FLYING PROGRESS

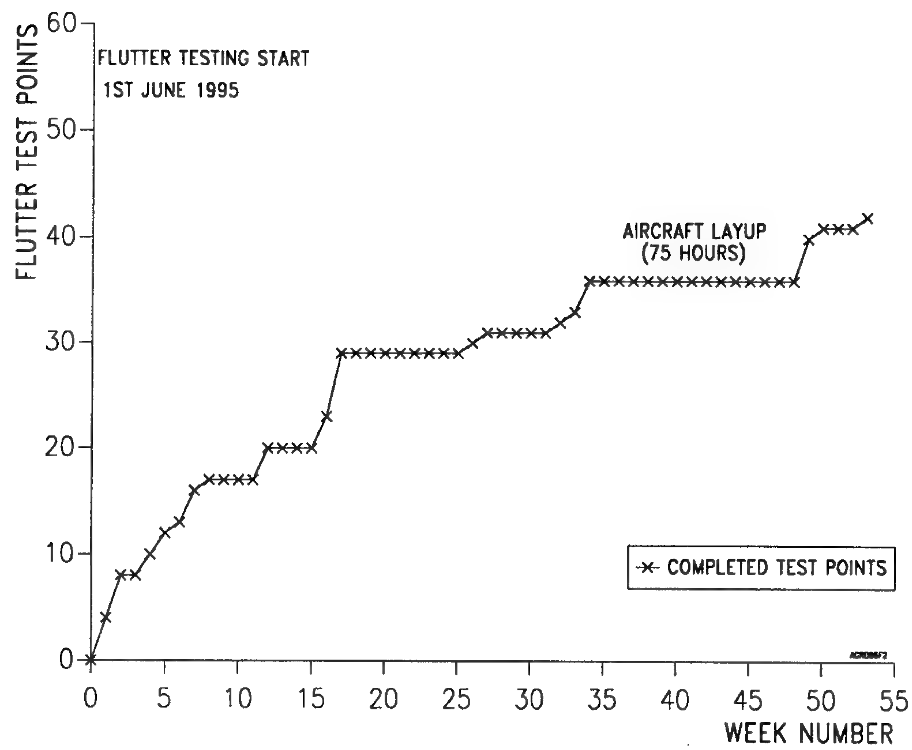


FIGURE 10: FLUTTER TESTING PROGRESS

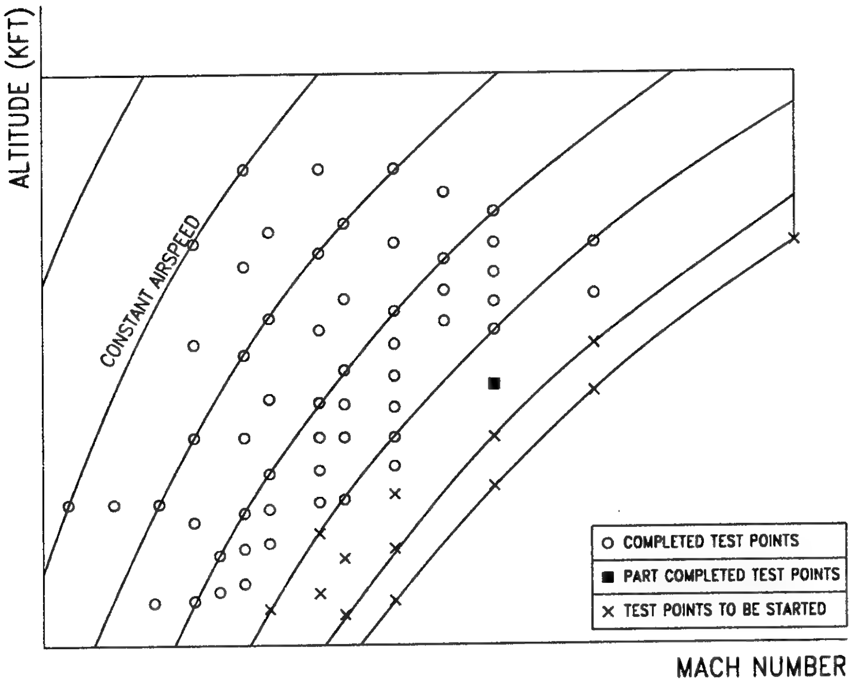


FIGURE 11: SUMMARY OF FLUTTER TEST POINTS

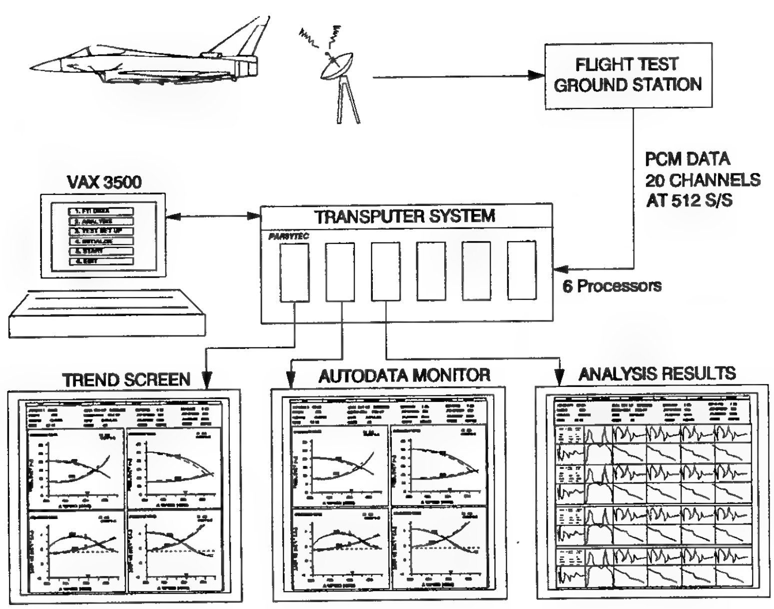


FIGURE 12: FLUTTER GROUND STATION

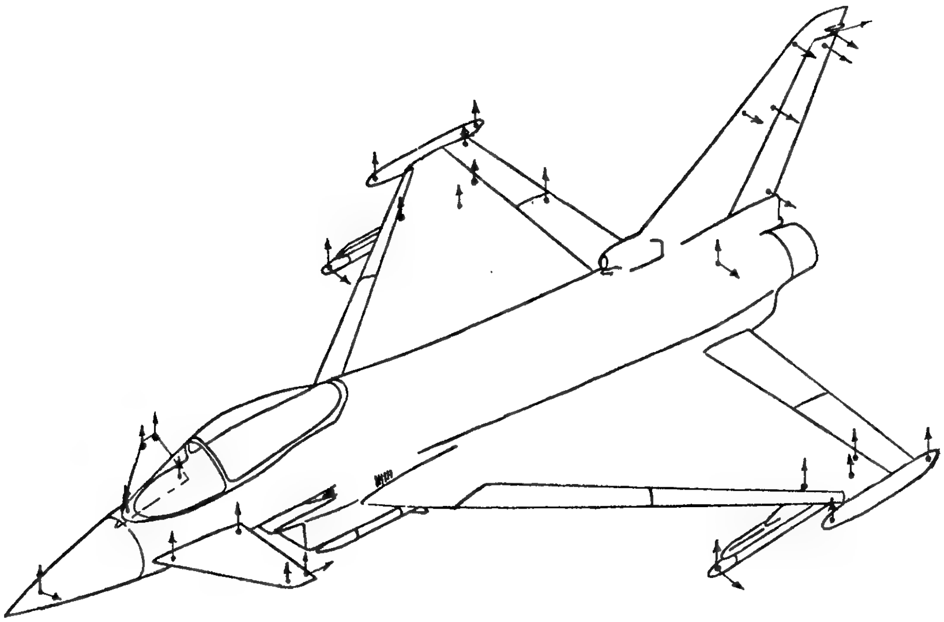


FIGURE 13: FLIGHT TEST INSTRUMENTATION

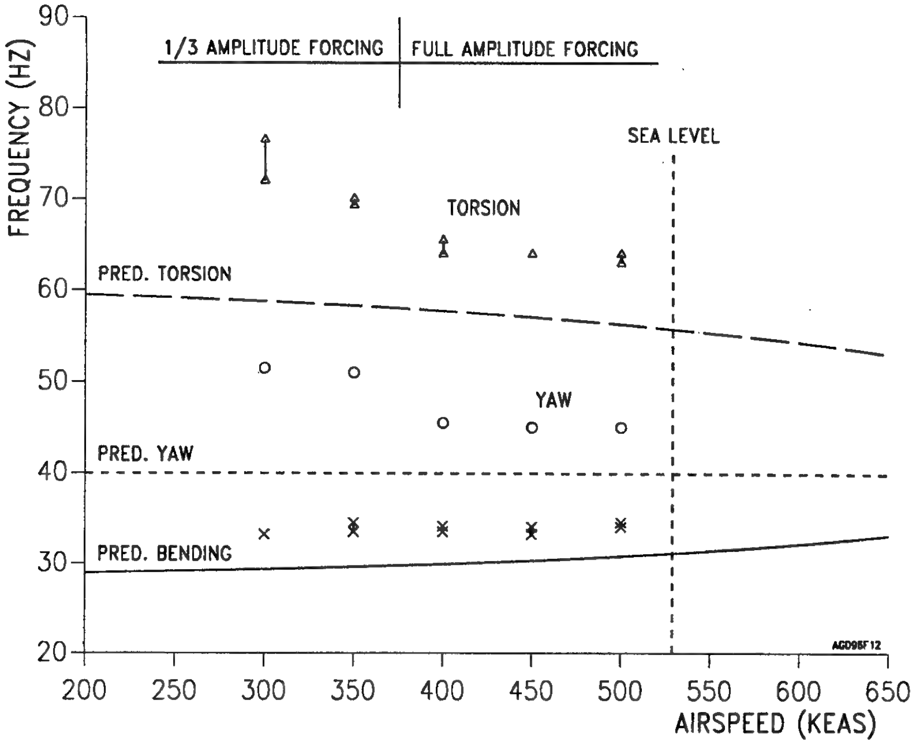


FIGURE 14: FOREPLANE FREQUENCY TREND M=0.8

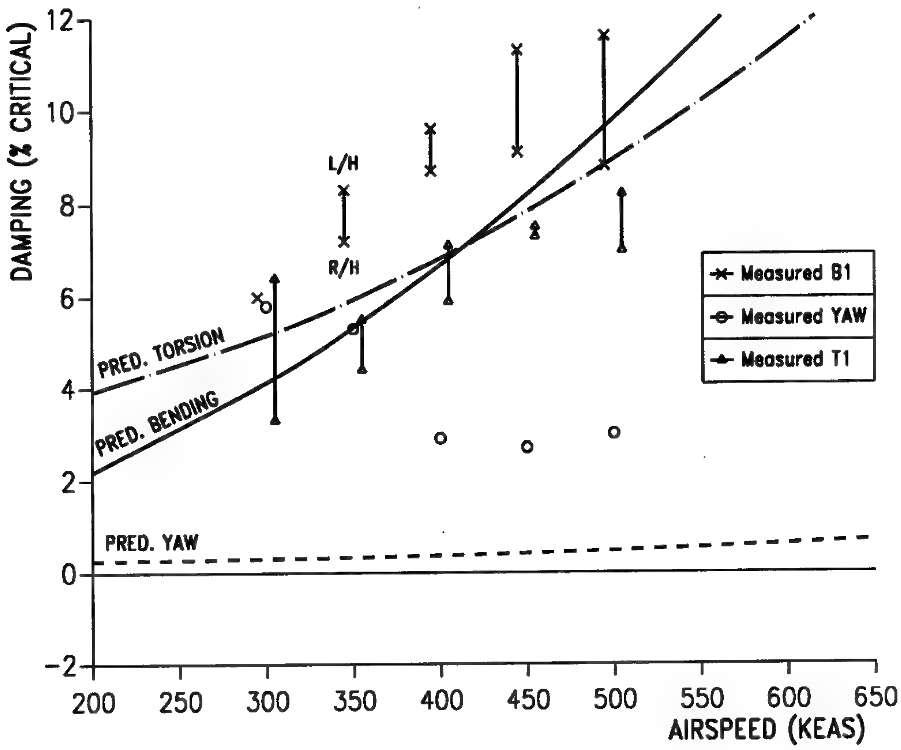


FIGURE 15: FOREPLANE DAMPING TREND M=0.8

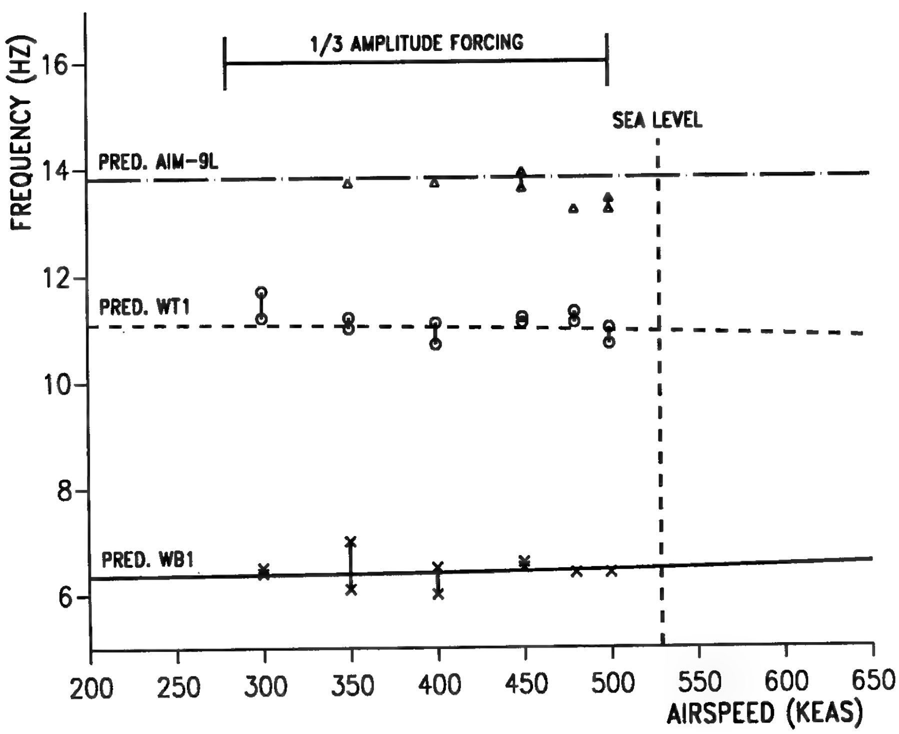


FIGURE 16: WING FREQUENCY TREND M=0.8

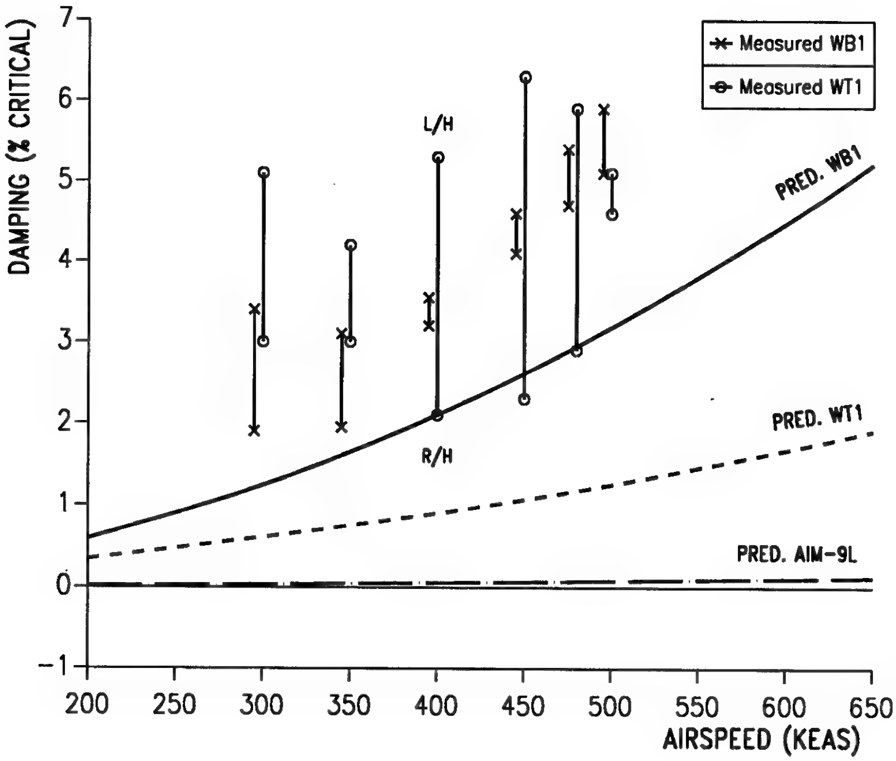


FIGURE 17: WING DAMPING TREND M=0.8

REDEFINING FLIGHT TESTING: INNOVATIVE APPLICATION OF THE WORLD WIDE WEB

Michael C. Hughes, Computer Sciences Corporation
Lee S. Gardner, Darcy S. Painter, Air Force Flight Test Center (AFFTC)
306 East Popson Avenue
Technical Directorate, 412th Test Wing
Edwards Air Force Base, California USA 93524

Summary

Application of World Wide Web technology to Flight Test is discussed. Examples of how efficiencies in processing flight test data have been gained using an "Intranet" are presented. The Air Force Flight Test Center has successfully used an Intranet to reduce the support staff for post-flight data processing by 90% over the past four years. Techniques are discussed, illustrated by examples, to demonstrate that Intranets have broad application to the Flight Test business. The application of Web technology to manage financial data in the EDGE project is discussed.

List of Symbols and Acronyms

AFFTC: Air Force Flight Test Center
E-MAIL: Electronic Mail
EDGE: Electronic Data Generation & Exchange
FTE: Flight Test Engineer
HTML: Hypertext Markup Language
IT: Information Technology
OO: Object Oriented
RDBMS: Relational Database Management System
Web, W3, WWW: World Wide Web

1 Introduction

The past few years have forced dramatic changes in the world of flight testing. With the changing world order has come new pressures to test weapons systems as economically as possible. Flight test organizations are coping with shrinking budgets, eliminating personnel, while simultaneously reducing test cycle time and improving competitiveness. Although these changes have been painful, they have also presented unique opportunities. The same factors that make surviving in business difficult have become productive forces for reengineering and improving business by leveraging technology.

It has been evident for many years that flight test customers want more, better, cheaper, faster flight test results NOW! Since flight testing is an information-based business, there were expectations that Information Technology (IT) would be the silver bullet that slays the monster[1] of high costs and long cycle times for flight test customers. The first generation of IT in the 1980's brought Relational Database Management Systems (RDBMS). In this decade, Object-Oriented (OO) methods promised great improvements. However, none of these innovations have yet resulted in

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

order-of-magnitude improvements in flight test productivity.

The problem is that processes are much more complex and interdependent than anyone realized. The RDBMS and OO, thought to be total solutions, addressed only limited aspects of information processing. RDBMSs allowed the making of effective storage places for data and information. An RDBMS could be designed so that data could be put in and later retrieved in a manner that was useful to flight testers and their customers. But, RDBMS only automated data storage and retrieval, not entire information-producing processes. Likewise, OO only improved software creation processes and quality, incrementally, not the order-of-magnitude improvements flight test customers wanted. Together the combined impact of OO and RDBMS still have not delivered sufficient power to transform the flight test business.

This paper explores the World Wide Web (WWW) as a transformational force in redefining the flight testing business. Most WWW applications developed today are to share information or create virtual market places. But, this technology has greater power and utility than simply selling products. From an economic perspective, the most useful application of WWW technology may be in enabling businesses to dramatically cut their costs, and thereby become more competitive. At the AFFTC, while we are actively pursuing the marketing power of the WWW, this paper concerns the power of the WWW focused internally, as an "Intranet." Web technology applied internally to the infrastructure, enabling people to access data and move between systems more easily, has changed what is done inside the organization. Workflow facilitating systems, built using Web technology, have been created that have resulted in dramatic reductions in personnel and in data product cycle time.

In this paper we will describe how these application evolved, how results were achieved and how the WWW tools provide the key to transforming flight testing into a paperless business. Finally, we will describe how the WWW has provided an opportunity to leverage flight test information processing capabilities and apply innovations to other types of information to create a more flexible, effective and competitive business entity.

2 History

Before use of WWW technology was introduced at the AFFTC, the processing of flight test data was a complex, knowledge-intensive business. Standard data formats and data analysis software had been developed in the 1970's and 1980's, but the production of custom data products (plots, tabular listings, data sets, data bases) for the various AFFTC flight test customers was still primarily a manual, personnel-intensive job. In the Range Division, the central data processing function for AFFTC customers, the data analysis ran on a mainframe computer, directed by hand-developed scripts, and controlled by 34 personnel via remote terminals.

With the advent of the personal computer and the workstation, the homogeneous mainframe computing environment changed forever. By 1988,

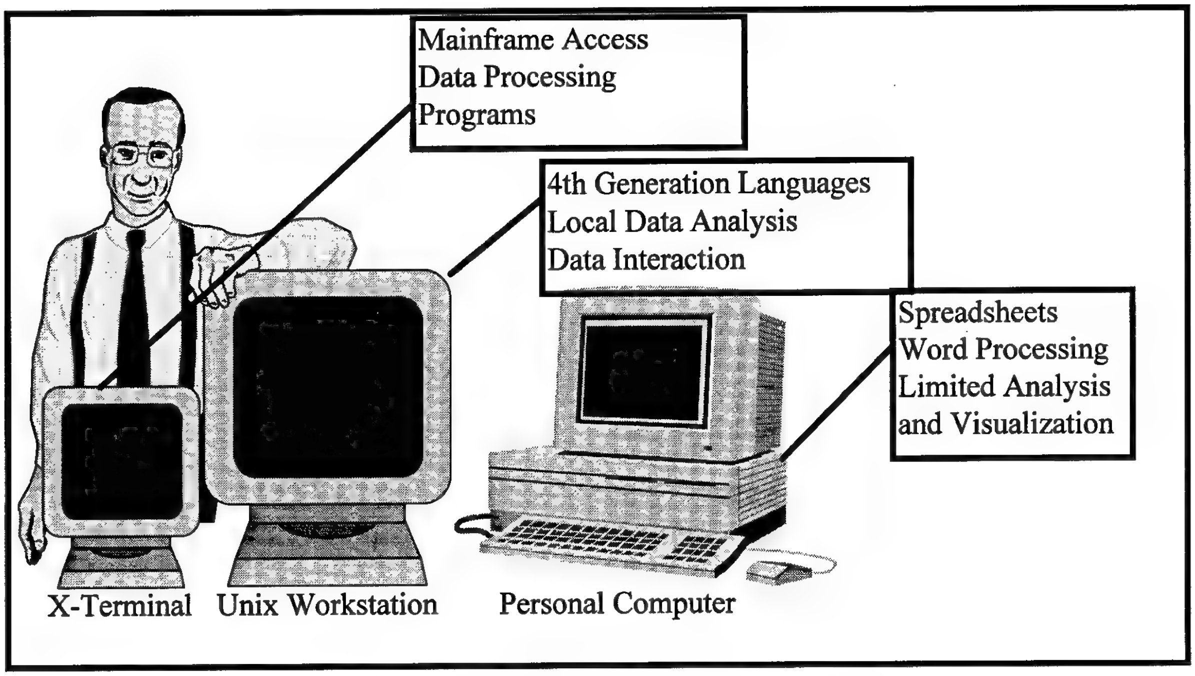


Figure 1: The FTE's Data Environment (Past)

data processing users were asking for their own access to data analysis and data product-producing software. User demand to access software tools using their machines continued to multiply as their workstations became more powerful, but integrating new computing platforms into the mainframe-oriented computing environment was a difficult, complex task. New user interfaces had to be developed for each new computer-type adding to what was rapidly becoming a flight test data analysis network. Users had to learn many different computers, operating systems and networking protocols to process their data. Figure 1 shows a typical user's labor-intensive environment.

This environment had three major problems which added significant cost and cycle time to the end result: The user had to know computer-specific knowledge (languages, operating systems, etc.) ancillary to Flight Test Engineering to get results; transporting data between the mainframe, Unix, and PC environments was difficult, complex, and required manual intervention; and writing software that could be ported across these platforms and scaled according to user needs was expensive. The Flight Test Engineer, FTE, wanted and needed the environment shown in Figure 2, a single interface to accomplish all computer-related tasks.

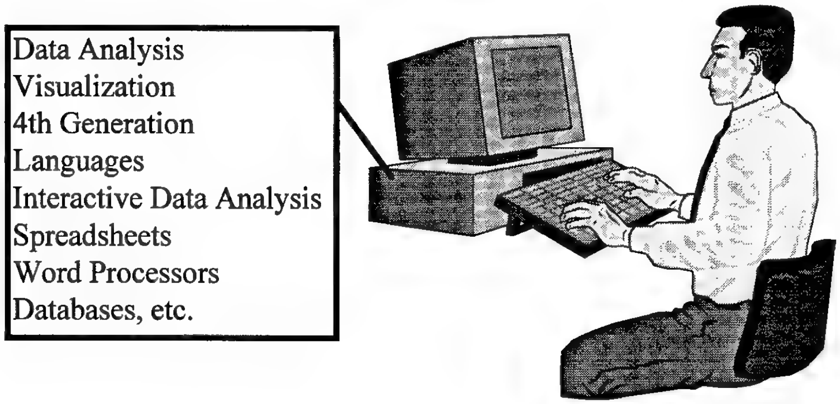


Figure 2: FTE Desktop (Present)

Fortunately, in the early 90s', just as the economic pressure on the data production personnel at the AFFTC was escalating, new technologies were emerging on the world stage that offered cost saving alternatives to the way data processing had been done in the preceding decades. AFFTC data production personnel realized that Web technology offered a platform independent, single interface solution with programmable business rules. A WWW browser, essentially a client to the software server located distant from the user, could run on a PC, McIntosh or a Unix Workstation. The server software, the actual data analysis code, and the data, could reside across the network on an appropriate computing platform. The WWW offered "universal readership[2]", meaning once information was available it was accessible from any type of computer, from any location, by any authorized person via a single interface. This was the capability exploited to redefine the data processing task at the AFFTC.

3 Data Processing Redefined

FTE clients now point their Web browsers at a hypertext markup language page to process flight test data. The steps involved to produce the desired data product are embedded in the server page. The client user is presented with a workflow chart, that describes any sub-task dependencies, offers help, provides prompting for required in-process information and/or decisions, and displays progress and status of the job. The scripts that specify the steps in the processing and issue the commands that do the processing are now developed for the server only, and are activated with user commands received from the HTML page viewed by the client with their browser.

The server runs the data analysis software and the HTML server software linked via Unix scripts, utilities, and tools. Each client runs browser software, which offers a universal interface access to all types of users and systems, as shown in Figure 3.

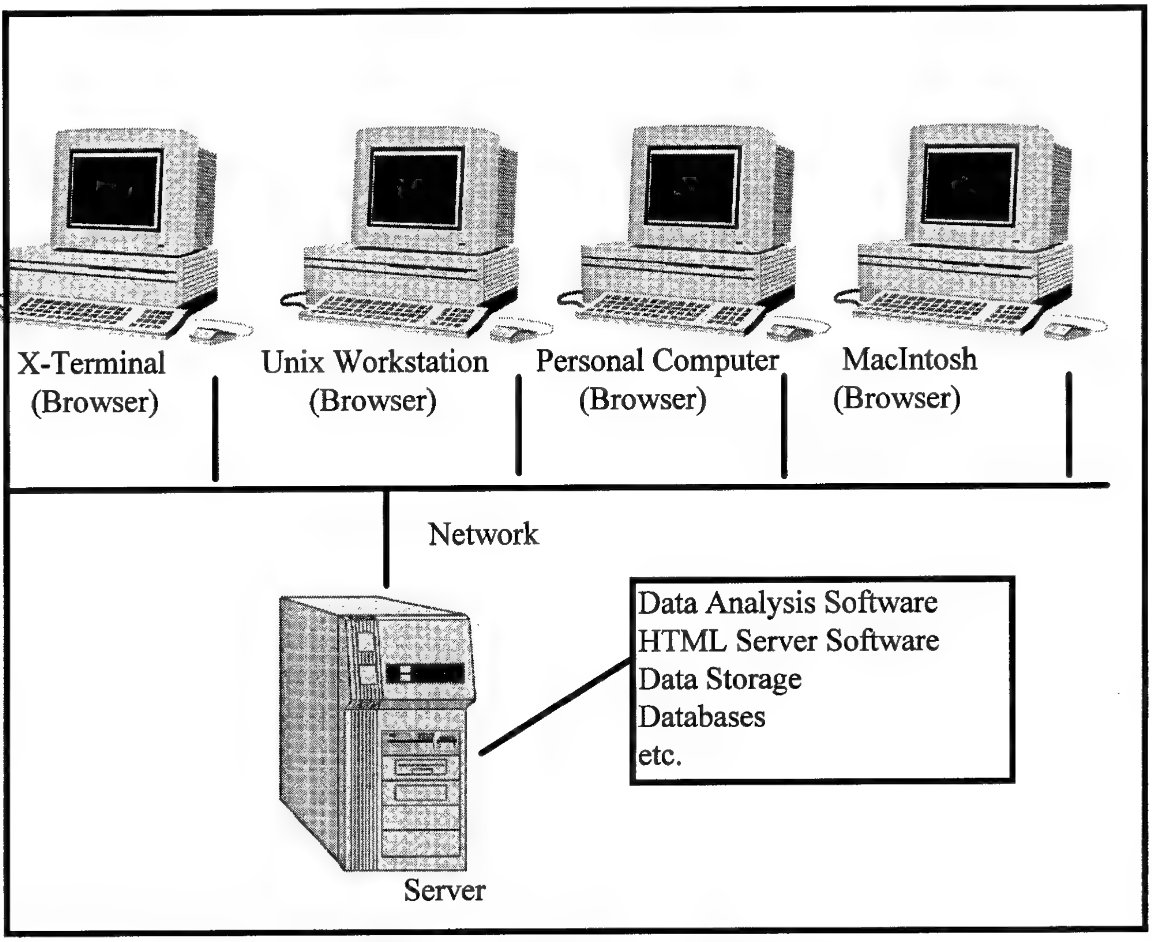


Figure 3: Clients and Server Configuration

4 Results Achieved

By using the client-server architecture and the WWW technology described above, a functional, post-flight data processing workflow system has been created. This system has three key benefits over its mainframe-based predecessor. First, it allows the customer, the FTE, direct access to data processing, analysis, and visualization software and flight test data from a single interface on their desktop, regardless of what type of computing platform that may be. The FTE is no longer required to spend time and energy learning ancillary computer languages, operating systems, etc. Second, with business rules captured and encoded on the server the manual labor required to move and process the data between systems is eliminated. Third, with more customer involvement, a single target system for software development, and a single user-interface development environment, less workers are required to produce more data products - an order of magnitude less. The implementation of the Intranet at the AFFTC for post-flight data processing has allowed supporting staff to shrink from 34 to just 3. The concept of producing more with less has actually been realized!

5 Financial Data Application

Post-flight data processing is not the only data processing application that might benefit from client-server architecture and WWW technology. Many other areas critical to flight testing

suffer from the mainframe mentality that has been the data processing paradigm since the 1960's. To explore the potential in these areas, the Business Electronic Data Generation and Exchange (EDGE) project was established.

The initial charter of the EDGE project was to tackle access to financial data, critical for effectively managing a flight test program. This data is stored in an RDBMS on a dedicated system. Even though the system is a relatively modern Unix workstation, data access was strictly via the mainframe paradigm, requiring special knowledge of the applications, operating system, and RDBMS software. This non-essential knowledge was ancillary to the financial manager just as a similar knowledge burden had been to FTEs in the post-flight data process. The EDGE project's first goal was to provide access to the data without requiring special knowledge.

The financial data application extracts raw data from the data storage system. The data is processed on the HTML server, again integrating utilities and custom-developed software. Next, the data is formatted to an HTML 2.0 standard and displayed on the user's client system. This can be any HTML 2.0 compliant browser. The number of steps have been reduced 50% from the old process to the new. More important than the reduction in the number of steps and the corresponding productivity improvement, are the simplification of the process and the reductions of the skill level required to run it. With the simpler process and lower skill level required, we have also reduced the risk of error by minimizing data entry.

The results of the application of the client-server architecture, a Web interface to the financial data, are impressive in a different way than the post-flight data processing application. The staff was not dramatically reduced. Instead, the availability of financial data has been improved by an order of magnitude. What used to take a full day or days to access and process in spreadsheets is now produced in 1 hour or less. In addition, where previously only a few people could actually access the data directly, the new application can allow a much larger group to benefit from its services. Since the data can be cached on the HTML server, the pages can be reserved, recreated, or the data may be reprocessed at a fraction of the original creation time.

6 Other Plans for EDGE

The advent of client-server architecture and Web technology have not overcome the mainframe-oriented paradigm of systems development. Many other flight test critical functions are controlled by these inaccessible, hard-to-use systems. Included in this group are training acquisition and management, inventory management systems, library management systems, personnel data management systems, aircraft maintenance management systems, range scheduling systems, etc. To a greater or lesser extent, all of these systems are candidates that might also obtain order-of-magnitude improvements just as post-flight and financial data processing have.

Currently, the EDGE project is looking at potential benefits in the training area. Five years ago a commercial training database system was purchased to fill a workflow management function for the on-base training organization. This RDBMS was designed from the mainframe paradigm where labor to enter information into the system was cheap and plentiful and the system was isolated. Two years ago a massive effort was undertaken to collect (on paper) a complete list of all training requirements for all AFFTC employees. Every employee researched training templates, prioritized, and indicated a preferred time frame for all required courses. The information was collected and handed in to the Training organization for manual entry into an RDBMS. As might be guessed, most of the information on the paper forms is still waiting input into the data management system and is no longer current.

The EDGE team has proposed a different solution to the problems of keeping employees' training needs current, maintaining employees training history and shifting the responsibility for keying in training to those who will reap the benefit, the individuals themselves.[3] Essentially, an on-line transaction processing system using client-server configuration, Web technology combined with electronic mail, is being proposed to replace the current paper based training system. In the paper based system the information is entered piecemeal in stove pipe RDBMSs owned by each of the process owners until the very end of the process, when all the information is entered again in another stove pipe RDBMS owned by the Training organization. In the new paradigm, the on-line transaction begins with the employee initiating a work flow process. Using e-mail/web technology the employee submits a request for training to the process handler (server) which distributes and monitors the task. Metrics are gathered automatically and the information, if approved, is published for management review through a web server. This publication is handled transparently as a background task thereby reducing manpower in managing the server content. Using the work flow model, business rules can be applied to enforce management approval of request and, if necessary, bypass non-essential steps after a pre-determined period of time. The entire process is controlled by the server without operator intervention. Once the course is completed the employee submits a review throughout the e-mail/Web interface completing the task and closing out the job. If the employee fails to submit the review their supervisor is notified by e-mail of the failure. The employee's report, complete with recommendations, is also on-line, readable by anyone who is interested in this particular training, with electronic mail notification to each of the members of the chain-of-command who approved the employee to attend the training initially. This then becomes a complete life-cycle record for each training class requested. Metrics are kept throughout the process, and the process owners are able to measure and track the success of their training program.

7 Conclusions

In the past few years we have witnessed a dramatic turnabout in flight test. The

change in the world order has brought huge pressures on flight test organizations to streamline their operations, lower their costs and increase their competitiveness. For the AFFTC, the urgency to "do more, with less" has become a rallying cry to reengineer our processes by the applying cutting edge technology to reduce data processing cycle time and free up our most valuable assets - our personnel, so that they can tackle the hard problems. The lessons learned in applying Web technology to such an information intensive business as flight test data processing are being leveraged to other basic business processes of flight test, resulting in reductions in cycle time, manually attended processes and the bottom line of how much it costs to flight test a weapons system at the AFFTC. Order-of-magnitude decreases in personnel and increases in productivity have already been demonstrated by innovative application of web technology.

---

[1] Brooks, Frederick P. Jr., "Preface to the 20th Anniversary Edition", "The Mythical Man-Month, Essays on Software Engineering, Anniversary Edition", pg. vii.

[2] World Wide Web Consortium, hosted by Laboratory of Computer Science at Massachusetts Institute of Technology, "http://www.w3.org/pub/WWW/Talks/General/Concepts.html".

[3] Hammer, M., "Reengineering Work: Don't Automate, Obliterate", in "Harvard Business Review", July-August 1990, No. 90406, pg. 109.

ESSAIS EN VOL DE L'A300-600-ST "BELUGA"

Guy DESTARAC
AEROSPATIALE - Branche Aéronautique
Direction des Essais en Vol
316, Route de Bayonne
31060 TOULOUSE Cedex 03 - FRANCE

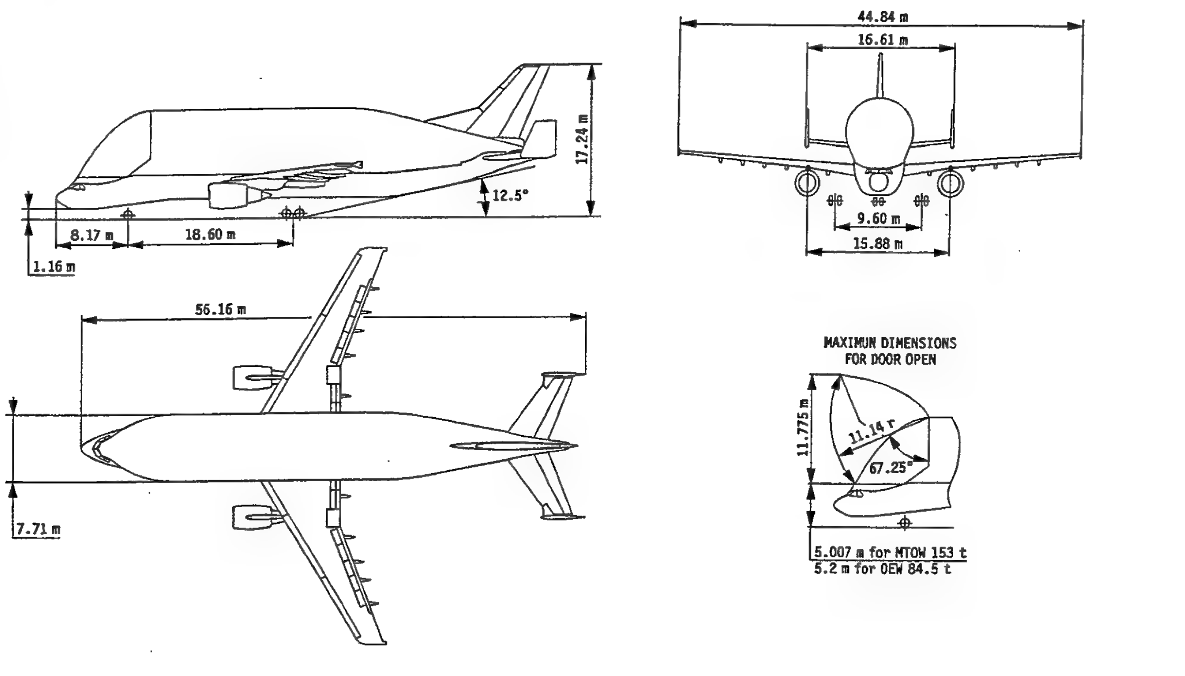
RESUME

Les Essais en Vol de l'A 300-600 ST «Beluga» avion, construit par Aerospatiale et Daimler Benz Aerospace Airbus, ont été confiés à la Direction des Essais en Vol de la Branche Avions de l'Aerospatiale.

Ce papier décrit l'installation de mesure et les outils mis en place sur le premier avion pour les essais en vol de développement et certification. Il montre les moyens utilisés pour le traitement et l'acquisition des données.

Le bilan fait en fin de campagne d'essais montre que: les bonnes surprises rencontrées sur le comportement de l'avion en vol, ont permis de compenser le temps pris par là résolution des problèmes de structure, le développement du système de chargement a pris plus de temps que prévu mais n'apas retardé les vols de certification qui ont été terminés fin juillet 1995.

DIMENSIONS AVION



Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

INTRODUCTION

L'Airbus Super Transporter A 300-600 ST «Beluga» est un avion construit à partir d'un A 300-600 R pour remplacer les Super Guppy utilisés pour les transports de tronçons d'avion entre les différentes usines du programme Airbus.

Les dimensions de la soute principale : 37,7 m de long, 7,4 m de diamètre font de cet avion l'un des plus gros de sa catégorie.

Sa construction a été coordonnée par un groupement d'intérêt économique «SATIC», Société de droit français établie à parts égales par Aerospatiale et Daimber Benz Aerospace Airbus.

La responsabilité des essais en vol a été confiée à la Direction des Essais en Vol de l'Aerospatiale, avec une équipe comprenant des personnels détachés du partenaire allemand. Le campagne d'essais a commencé par un premier vol d'une durée de 4 h 22 le 13 Septembre 1994 avec Gilbert DEFER Pilote (Directeur des Essais en Vol avions Aerospatiale), Lucien BENARD Copilote, Jean-Pierre FLAMANT Mécanicien navigant, Didier RONCERAY Ingénieur navigant d'essais. La certification en vol a été terminée le 24 juillet 1995, après 335H de vol, 21H de plus ont été nécessaires pour les démonstrations opérationnelles, le vol client a eu lieu le 19 octobre 1995 en cloture du programme.

Bien sûr cet avion n'est pas complètement nouveau puisqu'il a gardé la voilure et les systèmes de l'A 300-600 de base. Cependant la nouvelle forme et les dimensions du fuselage transforment radicalement son aérodynamique, sa structure aux dimensions impressionnantes est à surveiller, ses qualités de vol sont à vérifier en fonction des différents cas de chargement et en particulier de la position du centre de gravité qui peut être beaucoup plus haut que celui d'un avion normal.

INSTALLATION D'ESSAIS EN VOL

L'installation d'essais en vol installée sur le premier avion pendant la compagne d'essais de développement et de certification comprend environ 1000 chaînes de mesures. Le tableau ci-dessous qui donne le nombre de point de mesure par système avion montre qu'elle est très fortement orientée sur la surveillance de la structure de l'avion et de la porte cargo, de l'aérodynamique des parties modifiées, cela représente 60 % des chaînes de mesure. (Le reste étant utilisé pour les qualités de vol et la surveillance des systèmes).

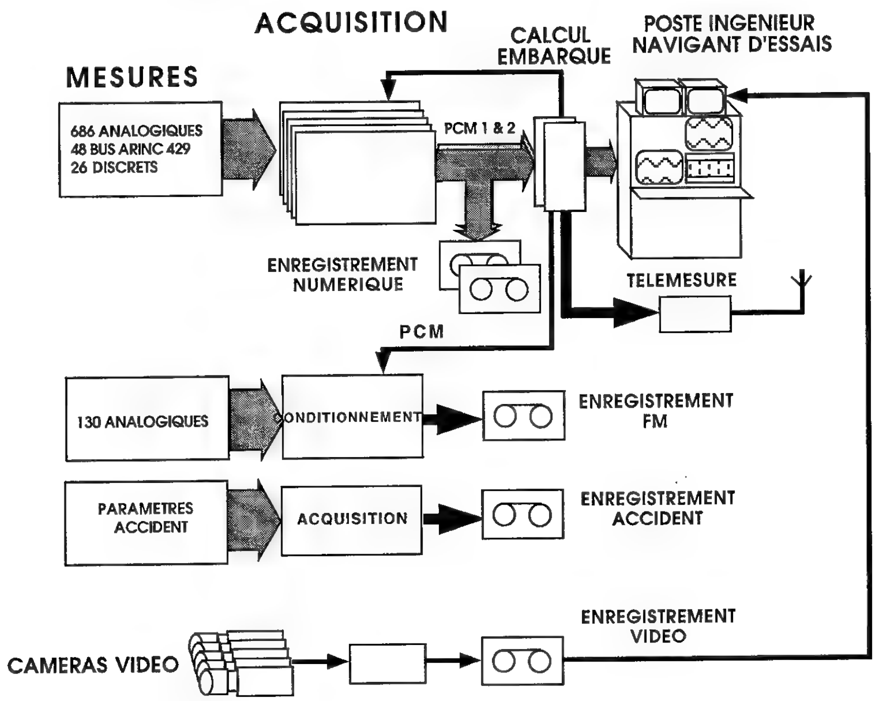
Le système d'acquisition et d'enregistrement qui est monté sur cet avion est dérivé de celui installé pour les essais des Airbus A 330/340. Les paramètres dont la bande passante est inférieure à 100 Hz sont mis sous la forme de deux messages PCM de 64 000 mots de 12 bits par seconde. Ces messages sont enregistrés en parallèle sur deux enregistreurs magnétiques, ils sont également envoyés sur le calculateur embarqué.

Ce calculateur embarqué fournit en temps réel toutes les informations nécessaires à l'Ingénieur navigant pour la conduite des essais et la surveillance de l'installation de mesure. A partir des PCM 1 et 2, il établit également un PCM Télémesure de 64 000 mots de 12 bits par seconde qui est envoyé au sol pour traitement temps réel. Un PCM lent est également produit et envoyé vers le système FM pour synchronisation avec les paramètres généraux de vol. Des paramètres élaborés à partir des mesures de base sont également produits (ex : masse, centrage, débits d'air,...), ils sont utilisés par l'Ingénieur navigant, ils sont également introduits dans le système d'acquisition pour enregistrement.

A 300-600ST -CHAINES DE MESURE

ATA CHAPT.	TITRE	ANAL. PCM	ARINC 429	MUX	COMP.	ON OFF PCM	ANAL. FM	MISC.
1	VOL	6			3			
2	AERODYNAMIQUE	12	5	31	10			
21	CONDITIONNEMENT D'AIR	93			11	2		1
22	PILOTE AUTOMATIQUE		18		17	14		
23	RADIOCOMMUNICATIONS	1						4
24	ELECTRICITE	15						2
27	COMMANDES DE VOL	38			14		7	22
28	CARBURANT		1					
30	PROTECTION GIVRE							6
31	INDICATIONS		8					15
32	ATTERRISSEURS	12			1	5		6
34	NAVIGATION		12		1			24
36	PRELEVEMENTS D'AIR	3			2			
49	APU	13			4	1	1	
50	CHARGES, CONTRAINTES,VIBRATIONS	413		6	19		116	7
52	PORTES	72						
71	MOTEURS	8	4	8	1	4		16
	TOTAL:	686	48	45	83	26	124	103

A300-600ST - INSTALLATION D'ESSAIS



Pour la conduite de l'essai, l'Ingénieur navigant utilise deux écrans qui lui fournissent les paramètres généraux de vol d'une part et les mesures liées à l'essai en cours d'autre part. Un système de «hard copy» et un enregistreur graphique permettent de conserver une trace papier des évolutions de certains paramètres.

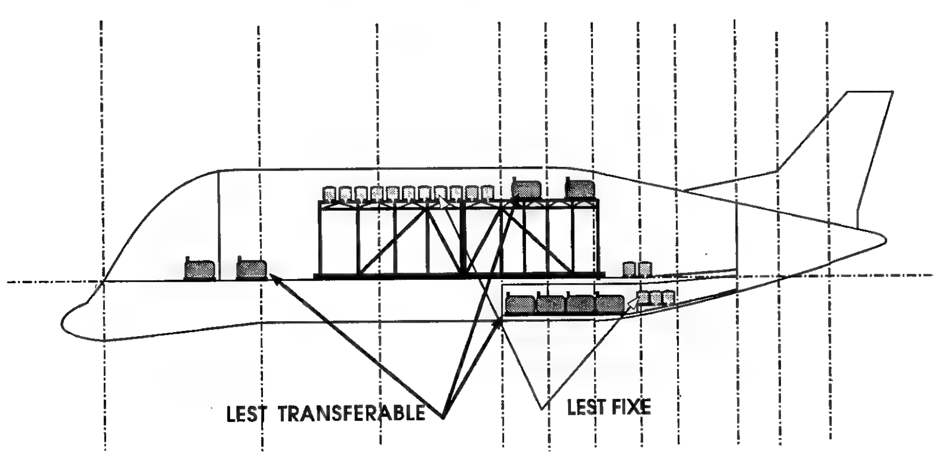
Les paramètres à bande passante élevée (bruit, vibrations, transitoires électriques) sont enregistrés en analogique FM.

Un système enregistreur d'accident permet de conserver les principaux paramètres avion en cas de problème majeur.

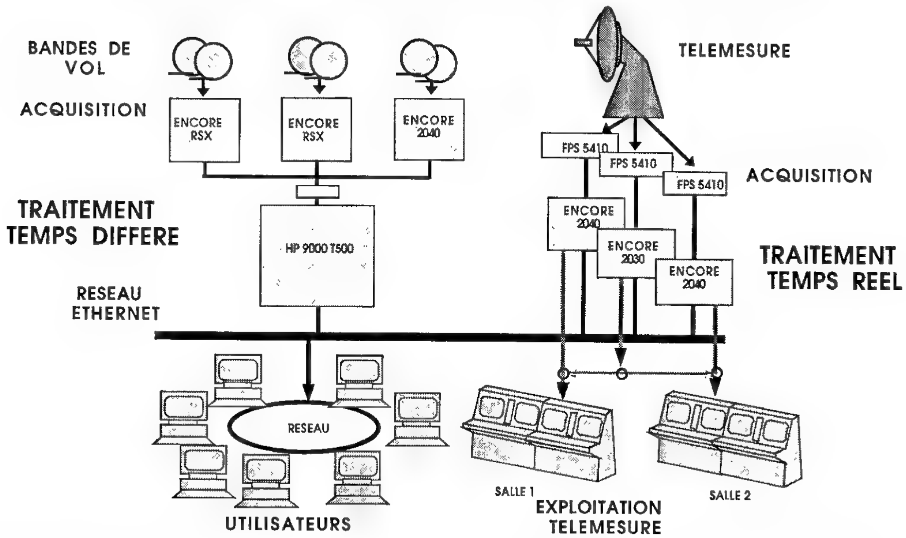
Pour la surveillance des essais en conditions givrantes naturelles, un système vidéo comprenant huit caméras est installé et est complété par les mesures traditionnelles de caractéristiques du nuage (teneur en eau , grosseur des gouttelettes).

Pour assurer les vols dans toutes les conditions de masse et de centrage, du lest est installé dans la zone cargo. Une partie est fixe, l'autre est transférable en vol entre des bidons placés à l'avant et à l'arrière de l'appareil et permet de faire varier la position du centre de gravité sur l'axe longitudinal, mais aussi, pour la première fois sur cet avion, sur l'axe vertical à l'aide de bidons placés très haut dans le fuselage. Ce dispositif permet de progresser dans l'ouverture du domaine de façon plus sûre mais il permet aussi de gagner du temps en testant plusieurs cas de chargement dans le même vol.

A300-600ST - CHARGEMENT POUR ESSAIS EN VOL



AEROSPATIALE - TRAITEMENT DES DONNEES D'ESSAIS EN VOL



<u>**TRAITEMENT DES DONNEES, ANALYSE:**</u>

Les essais en vol ne sont complets que si l'évaluation de l'équipage est confortée par les résultats de mesures pour cet avion, deux méthodes sont utilisées :

- le traitement temps réel en Télémesure, le plus rapide, particulièrement bien adapté aux essais de qualité de vol, à la surveillance de la structure et aux essais de charge, aux essais de flottement («flutter»).
- la lecture des bandes enregistrées à bord, plus classique, elle est utilisée pour tous les essais non traités en Télémesure et pour la surveillance des systèmes.

Ces deux moyens complémentaires font largement appel à un système de calcul à base de calculateurs temps réel (Encore) bien adaptés au traitement continu des données. La partie traitement scientifique et gestion des données étant assurée par un calculateur HP 9000 travaillant dans le monde UNIX. Leur réseau de stations HP (ex Apollo) permet aux différents spécialistes de faire tous les traitements nécessaires à partir de stations de travail situées dans leurs bureaux.

<u>**PROGRAMME D'ESSAIS EN VOL:**</u>

Le programme d'essais, était prévu pour durer onze mois et demander de l'ordre de 400 heures de vol.

Il était construit en cinq phases :

<u>Phase 1</u> : ouverture du domaine de vol, vérification de l'avion et de ses systèmes, premières estimations des qualités de vol et des charges structurales.

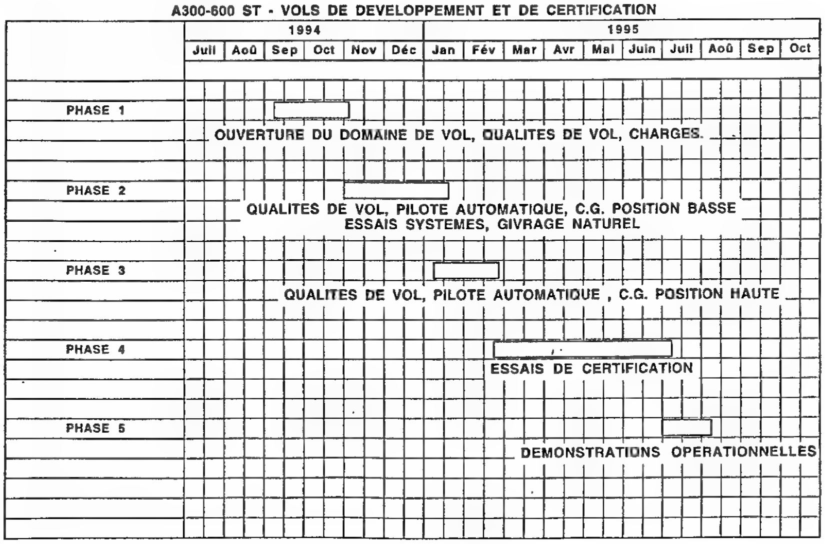
<u>Phase 2</u> : essais de qualité de vol, de performances, de pilote automatique avec centre de gravité en position basse, essais système, essais en conditions givrantes.

<u>Phase 3</u> : essais de qualité de vol, de pilote automatique avec centre de gravité en position haute.

<u>Phase 4</u> : essais de certification

<u>Phase 5</u> : démonstration en conditions opérationnelles.

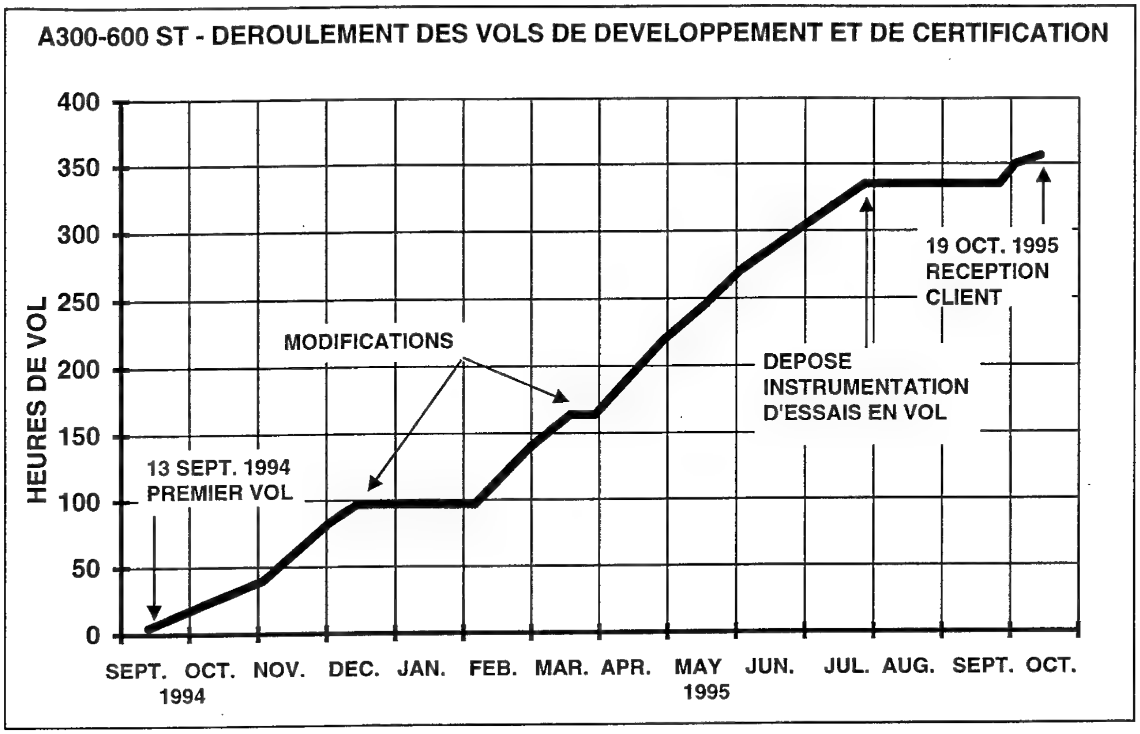
A300-600 ST - VOLS DE DEVELOPPEMENT ET DE CERTIFICATION



DEROULEMENT DE LA CAMPAGNE D'ESSAIS:

La bonne disponibilité des systèmes avion a permis un déroulement de la campagne dans les délais prévus. Elle n'a été arrétée que pour les chantiers de modification structurales en janvier et en mars 1995 avant le début des essais de certification qui ont été terminés fin juillet.

Les démonstrations opérationnelles qui étaient prévues initialement en juillet n'ont pu être effectuées qu'en septembre après une mise au point plus longue que prévue des systèmes de chargement bord et sol.



A300-600 ST - HEURES D'ESSAIS PAR SYSTEMES AVION				
CHAPT. ATA	TITRE	HEURES DE VOL	CERTIF.	DEVELOPT.
0	GENERAL	11,32		11,32
1	VOL	128,00	50,30	77,30
9	BRUIT EXTERIEUR	3,20	3,20	
21	CONDITIONNEMENT D'AIR	13,00	8,40	4,20
22	PILOTE AUTOMATIQUE	52,15	38,25	13,50
23	COMMUNICATIONS	3,25	3,25	
24	ELECTRICITE	2,05	0,20	1,45
26	PROTECTION FEU	1,20	1,00	0,20
27	COMMANDES DE VOL	11,30	5,00	6,30
29	HYDRAULIQUE	1,30		1,30
30	PROTECTION GIVRE	6,10	6,10	
32	TRAINS FREINS	5,35	1,00	4,35
34	NAVIGATION	17,35	14,15	3,20
49	APU	8,30	1,45	6,45
51	STRUCTURE	23,25		23,25
52	PORTES	0,55		0,55
53	FUSELAGE	13,40		13,40
	DEMONSTRATIONS	48,13		48,13
	TOTAL:	356,05	136,50	219,15

Le bilan en fin d'essais en vol de cette machine montre que:

- les qualités de vol de l'avion sont plutôt meilleures que prévu, en particulier en latéral à incidence élevée où les prévisions des bureaux d'études étaient très pessimistes.

- Le chargement avec position haute du centre de gravité donnent des qualités de vol qui restent très acceptables.

- Le «yaw damper» a du être adapté pour améliorer le comportement en turbulence mais les réglages corrects ont été rapidement trouvés.

- Le programme d'essais de flottement a du être complété par des points de vol à centrage haut, en effet l'influence de la charge sur les modes de vibration fuselage et les déformées des outillages de chargement sont à prendre en compte dans le comportement de l'avion.

- Les principales difficultés ont été rencontrées au niveau de la structure des parties arrières (pointe arrière et plan horizontal) pour lesquelles les charges avaient été sous-estimées et qui ont du être renforcées.

-Un dispositif de bras de levier variable a également été installé sur la commande de la gouverne de direction.

- Une mauvaise surprise est arrivée au cours des essais d'atterrissage ou l'on n'a pas retrouvé les performances de l'avion de base avec un des types de pneus retenus.

- Le chantier de renforcement a retardé le programme d'environ un mois mais les bons résultats rencontrés en qualités de vol ont permis de rester dans les délais prévus.

- La mise au point au sol du système d'ouverture de porte et de chargement a été plus longue que prévue, les vols de démonstration n'ont pu avoir lieu qu'en octobre avec le transport de la première voilure A340 entre BREME et TOULOUSE , le 9 Octobre 1995, après dépose de l'instrumentation d'essais.

CONCLUSION

En conclusion, le programme de mise au point et de certification en vol de l'A300-600st s'est passé dans les délais, il a nécessité un peu moins d'heures de vol que prévu. La mise en place opérationnelle a été légèrement retardée par la disponibilité des systèmes sol mais l'ensemble répond aux exigences du client . L'organisation et le suivi mis en place ont fonctionné correctement dans le contexte de ce programme en coopération, avec deux partenairesmajeurs et un nombre important de sous-traitants.

THE CERTIFICATION PROCESS OF THE OPHER SMART MUNITION ON THE AMX AIRCRAFT

E. Petraroli
Divisione Aerea Studi Ricerche e Sperimentazioni
Reparto Sperimentale Volo
Aeroporto Militare Pratica di Mare
00040 Pomezia (Rome) ITALY
D. Israeli
Elbit Defense Systems Ltd.
Advanced Technology Center
Hof Hacarmel P.O.B. 539
31053 Haifa ISRAEL

SUMMARY

The Italian Air Force (ITAF) has been seeking a low cost smart munition capable to attack vehicular targets with particular reference to armoured vehicles and tanks.
Low cost implies a guided weapon such as a laser bomb. The main objections to a laser guided weapon, such as those ones belonging to the Paveway family, derived from two intrinsic limitations:

- laser bombs require an illuminator (not a fire-and-forget weapon);
- overall accuracy decreases drammatically with delivering energy.

On the other hand, adoption of a missile would have increased both integration and procurement costs.

So, it was decided to test the OPHER system in a different scenario with respect to that one which the system was originally designed for:

- the Italian scenario, characterized by Mediterranean scrub, could have affected system performance in a different way with respect to Israeli desert;
- the AMX can deliver weapons with an energy much lower than the F-4, on which this weapon has been employed in the Israeli Air Force;
- the AMX is equipped with a twin store carrier and the F-4 version of the OPHER system could not fit on it.

The result of the successful testing and analytical work described in this paper led to the certification of the OPHER smart munition on the AMX for the Italian Air Force.

1. INTRODUCTION

The OPHER system is an autonomous precision strike smart munition for day and night air-to-surface attack of tanks and various types of vehicular and marine targets. Once released from an aircraft towards a target area, the OPHER autonomously selects the target and guides itself until a hit is achieved.

A folding tail version of the OPHER system that includes improved aerodynamics and guidance was adapted and optimized to allow multiple carriage and deployment from the AMX aircraft with typical low energy release profiles.
The process of the OPHER certification, led by the Italian Air Force Flight Test Center, namely Reparto Sperimentale Volo (RSV), and supported by the various industries, included analytical work for the determination of operational envelope and test activities for the verification of the OPHER system autonomous performance for ITAF requirements.

This paper describes the various activities and results of the successful certification process.

2. BACKGROUND

2.1 OPHER System Description

The OPHER is an autonomous precision strike smart munition for day and night air-to-surface attack of various types of vehicular and marine targets. The OPHER system has autonomous capabilities to search, detect, acquire, track and guide itself to the targets, by implementing an advanced infrared image processing to select valid targets while ignoring clutter or decoy/countermeasure related objects.

This autonomous capability obviously has significant operational advantages over the common man-in-the-loop operations that require either target designation (laser) or data links and electronic interfaces of some sort with the aircraft systems. When combined with appropriate guidance and a MK-82 warhead the OPHER system offers a solution for several operational needs in the modern battlefield.

The Opher system is launched from the aircraft using a normal ballistic code for "Continuously Computed Impact Point" (CCIP) or "Continuously Computed Release Point" (CCRP) and follows a 2 phase trajectory:

- **Ballistic**
  During this phase the OPHER infrared (IR) seeker searches for the target while following a ballistic trajectory. At a certain point along this phase the system detects and acquires (lock on) the target within the Field of View (FOV), and starts the trajectory correction towards the target.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

The autonomous detection and acquisition of the target is achieved by implementation of a series of real time non linear two dimensional spatial algorithms/filters and an adaptive post processing of the infrared image that extracts valid targets from the clutter once a set of conditions and properties is met.

- **Terminal Guidance**
  Upon acquisition of the target, the OPHER system starts to guide itself in pursuit mode, nullifying the error between the velocity vector and the Line of Sight (LOS) to the target.

  The autonomous guidance in this phase is based on continuous real time LOS data received from the infrared image processor (target track) and implementation of iterative guidance algorithms which render the OPHER system robust to interferences.

The OPHER system time-event chart is shown in Figure 1.

2.2 Adaptation to AMX Operational Requirements

Prior to starting the certification process, the OPHER configuration was adapted to comply with the specific AMX operational requirements.

2.2.1 Operational Configuration

AMX operational requirement was to carry 2 OPHER systems on one Twin Store Carrier (TSC) - either on wing or belly stations. In order to achieve geometrical compatibility the span of tail and canards had to be decreased to 18 inch. In addition, an asymmetrical mirror tilt of 13 degrees inwards of each system mounted on the TSC was necessary. (See Figure 2).

As a result of the span decrease the system aerodynamic configuration had to be modified in order to provide the basic requirements during the following flight phases:

- **Release**
  The 18" span configuration is marginally stable. Therefore a folding tail was designed, which is triggered upon release from the bomb station and provides a stable airframe within a short period of time, allowing a safe release from the aircraft. The timing of tail fin opening process was designed to compromise two opposing constraints:

  - In order to achieve maximun stability the tail fins must be opened shortly after release.
  - In order to prevent collision contact of opening fins with the aircraft the tail fins should be opened as far away as possible from the aircraft.

  The result of the optimization is the tail opening time curve shown in Figure 3 and stability characteristics shown in Table 1.

  This design shows that within a short and well defined (narrow tolerance) period of time after release the configuration achieves about 90% of the maximum stability, while the actual span is not increased much and does not interfere with the aircraft structure since the fin angle is only 35 degrees.
  The time required to fully open the fins (70 degrees) is such that this happens at a safe distance from the aircraft.

- **Ballistic flight**
  During this phase the system should be capable of restraining quite quickly the oscillations resulting from the release phase transient. This was achieved by implementing a damper/spring mechanism on the servo canards.

- **Homing**
  The aerodynamic configuration in open position has to provide similar or better maneuverability relative to the original fixed tail configuration in order to assure same or better hit accuracy. Therefore opened fin aerodynamic configuration was defined to provide the aerodynamic parameters required.

The result of the above mentioned considerations is the configuration outline shown in Figure 4.

2.2.2 Low energy mission profiles

The original configuration of the OPHER system was designed for high energy profiles which are characterized by release velocities of 500-600 knots and hit angles of 35 degrees (from horizon) and above.
However, the AMX operational envelope and performance require mainly low-energy profiles which are characterized by release velocities below 500 knots (Mach number (M) below 0.75) and hit angles as shallow as 25 degrees from horizon.
Therefore the OPHER guidance had to be modified in order to provide the required hit accuracy for the low energy profiles as well.
This was achieved by implementing the Pulse Width Modulation (PWM) control of the canards that yields a pseudo-proportional canard torque and a proportional pursuit guidance rather than the original bang-bang system.
The PWM control gain and parameters were optimized using the OPHER six degrees of freedom simulation in order to get the maximum hit probability all over an operational envelope that includes both high and low energy profiles/missions.

2.2.3 Testing of the modifications

The modified configuration was tested is Shdema Range (Negev Desert) using an Israeli Air Force F-4 in low energy release conditions prior to starting the certification process with the AMX.
The flight tests in Israel verified:

- Captive flight envelope with F-4
- Proper function of the folding tail and timing.
- Safe release and behaviour.
- Proper ballistic flight trajectory.
- Optimun homing capability.
- Verification of 6 degrees of freedom (6DoF) simulation prediction.

3. OPHER-AMX CERTIFICATION PROCESS

The certification process included simultaneous analytical, simulation and test activities that were supported by ALENIA, ELBIT, FIAR and led by RSV. The activities included the following:

- Geometrical compatibility test.
- Pit Drop test.
- Operational configurations determination.
- Preliminary AirWorthiness Flight Limitations (AWFLs).
- Envelope and release tests.
- Final flight and release envelope determination and final AWFLs;
- Operational demo test;
- Additional analysis.

3.1 Geometrical compatibility and Pit Drop tests

On the AMX aircraft a suitable strong point is missing, since the only one present can hold up to 200 lb whilst the arming cables of both thermal battery and tail unfolding mechanism have a "shear link" that breaks the lanyard at the same value. So, it was necessary to develop a strong point to be installed on the retaining bolt of each Ejector Release Unit (E.R.U.).
It was also necessary to connect the thermal battery arming cable to an Arming Fuzing Unit (AFU) in order to get the control of battery and prevent the system from acquiring a potential target during emergency jettison. To connect the battery cable to the AFU, a standard swivel loop had to be added to the standard arming cable, as outlined in Figure 5.
A dressing scheme of the system on the aircraft is depicted in Figure 6.
Pit drop trials showed no problems in cable functioning.

3.2 Operational configuration determination

For the entire process one aircraft configuration was determined. This allowed to keep the integration costs low and, at the same time, to have the possibility to extend the flight clearances to other configurations through read-across with minor effort.

As far as safe separation is concerned, the worst bomb stations on the AMX are the outboard wing pylon and the underfuselage station, due to wing and twin store carrier respectively, which induce significant distorsions in the aerodynamic flow field. The latter is even worsened by the presence of a 1100 liters fuel tank on the inboard pylon.
For the mentioned reasons it was decided to pursue the a/c configuration depicted in Figure 7.

3.3 Airworthiness Flight Limitations for OPHER test flights on AMX

In order to release the development clearances a specific contract was signed between RSV and Alenia. Thirty-six test cases were investigated using the Safe Separation Trajectory Program (SSTP) developed by Alenia for the AMX program.
The test cases were aimed to clear a release envelope to allow both jettison during takeoff and release functions.
Additionally, in order to gain a full confidence on the results a sensitivity analysis was performed on 12 test cases, during which safe separation was investigated applying tolerances on angle of attack, normal load factor, Mach number and ejection force reduction. The effects of sideslip angle and tail opening malfunction were also highlighted.
Particular attention was devoted to determine the minimum release interval, which had to be increased when a two bomb configuration on the underfuselage station was used (partial a/c configuration).
A typical output of the SSTP can be seen in Figures 8 and 9.
The overall output of this analysis was used to determine flight release conditions for safe separation tests.

3.4 Safe separation flight tests

Two flights were carried out in order to validate the mathematical model and to extend the release envelope.
During the first flight, one system was released from the outboard wing pylon.
During the second flight two systems were released from the TSC on the underfuselage station, with the release interval determined for this critical condition.
Both releases showed a pitch down of the bomb higher than the predicted one (Figure 10), in particular when an adjacent store is present (TSC on the underfuselage station).
From the updated mathematical model this phenomenon was not considered critical neither for safe separation nor for system behaviour.

3.5 Certified flight and release operational envelope (Final Airworthiness Flight Limitations)

In order to match the mathematical model with the actual behaviour of the bomb, some contrivances were applied. The aerodynamic characteristics of the model were changed by:

- increasing the canards' instability contribution;
- modifying the aerodynamic coefficients' variation law as a function of the fin angle;
- increasing the pitch moment coefficient of the weapons released from both the outboard wing pylon

and the left station on the TSC (release with adjacent store installed);
- partitioning in a different way the total E.R.U. ejection force between the two pistons;
- decreasing the value of the damping coefficients.

With the mentioned modifications, simulation showed the mathematical model well matched the actual trajectories filmed during safe separation tests (Figure 11).
On this basis, release envelope could be extended up to max speed/Mach and dive angles similar to other external stores configurations.
The next step will be to evaluate and clear different aircraft configurations via read-across process.

3.6 Operational Flight Demonstration Test

3.6.1 Target set-up

Since damage to real tanks was not allowed a target simulator had to be built.
The target simulator had to represent a real target both in radiation intensity and distribution and spatial properties, since the system autonomous targeting algorithms process the IR image.
To satisfy these requirements an analysis and tests have been performed.

- The analytical part included the analysis of IR imagery collected previously in various tests. These data included a variety of target types like tanks, artillery, Armoured Fighting Vehicles, etc., and enabled the evaluation of the weapon operational flexibility to attack such targets. In addition, this analysis yielded the required foundation for the simulator design.
- The test part included measurement of radiation characteristics of targets in Italy, for different aspect and elevation angles, in order to verify some of the analysis conclusions.

Succesively, the simulator was built and validated during actual tests to yield the same properties as real targets when viewed by OPHER seeker.
For flight testing the simulator was positioned on a frame of an old tank located on the instrumented ground range in Sardinia.

3.6.2 Demonstration test

This test demonstrated the capability of the OPHER system to autonomously detect, acquire and home towards targets when delivered from an AMX in typical operational scenarios.
The demonstration took place over the Ground Test Range in Perdasdefogu (Sardinia).

- A/C configuration
  The aircraft configuration used is that one outlined in Figure 7.

- OPHER configuration (including telemetry)
  The system configuration was that one outlined in Table 2.

- Test scenario
  For demo flights both CCIP and CCRP modes have been used.

  For CCIP mode, a 30 degree dive attack was performed that implied a time of flight of the bomb of about 10 seconds. This condition is very critical for a guided weapon, since the resulting guidance time is quite short and, consequently, it is hard to make trajectory corrections.

  For CCRP mode, a level release at medium altitude has been performed. This condition is also critical, since velocity (energy) gain of the bomb is low. Additionally, a moderate crosswind was present, (around 30 knots with gusts), which should have worsened system performance.
  Release conditions for this mode were equivalent to the flight conditions the weapon would have at the top of its trajectory if released with a loft profile. This reduced safety traces on ground.

  Both releases were carried out at an airspeed around 430 KTAS (true airspeed), which is another critical condition as far as energy is concerned.
  For both releases, the loaded ballistic code was that one referred to MK 82 free-fall (FF), whose ballistics is slightly different from OPHER system. To take this difference into account, a "ghost" target was set at about 100 meters away from the real target.
  An additional study was performed in order to figure out how the MK 82 FF ballistic code could be suitable to release an OPHER system. This study, which took into account seeker FOV and bomb dynamics up to target acquisition showed that MK 82 FF balistics could be used for all OPHER releases but loft attacks. For the latter profiles a special ballistics shall be implemented in the aircraft software.

Figure 12 shows the detection rate of the target as a function of slant range along the trajectory.
Figure 13 shows guidance commands along the homing phase and proportional inputs given to the control surfaces can be seen.
Figure 14 shows the target position in seeker FOV coordinates from the first time the target entered the FOV until the hit. It can be seen that target position is kept near the FOV center (zero guidance error) for most part of the trajectory.

The demonstration showed that the OPHER system worked as predicted, when used in accordance with ITAF operational requirements.
The test demonstrated the performance of the OPHER system in all phases of flight and guidance, i.e.:

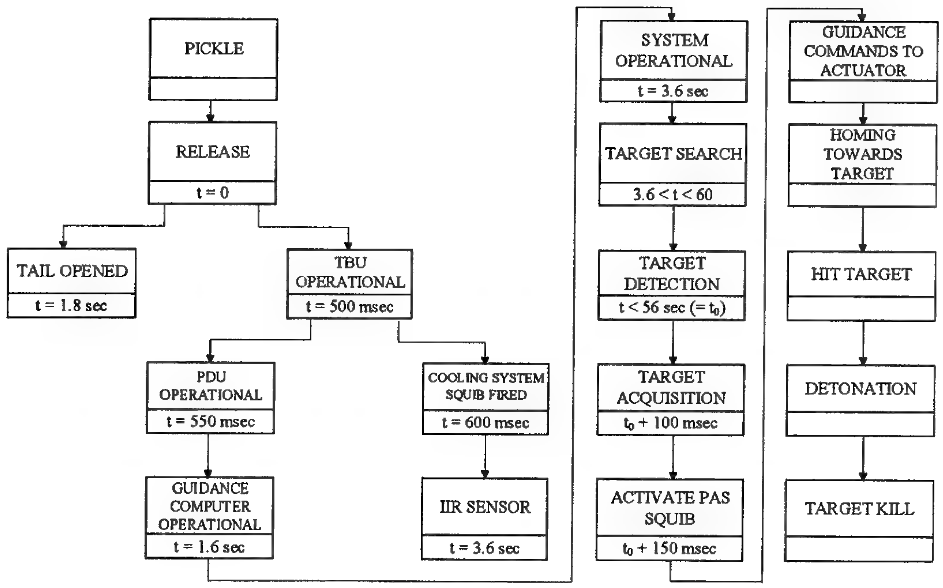


Figure 1. Functional flowchart of the OPHER system

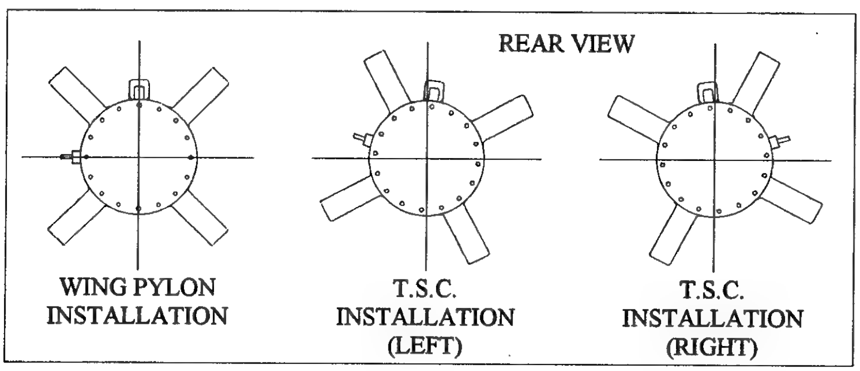


Figure 2a. Tail and guidance section tilt

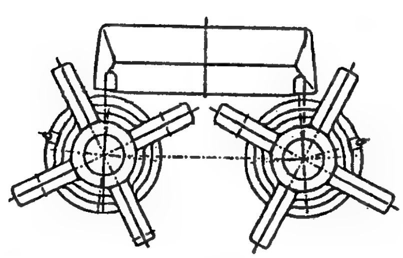


Figure 2b. TSC installation

- Detection and acquisition of the target.
- Tracking of target.
- Guidance and homing to the target.

The test was perfomed in conditions and modes that highlighted several operational advantages:

- Capability to launch in both visual (CCIP) and non visual (CCRP) modes.
- Capability to overcome and correct relatively large down range and cross range release errors (acquisition occurs at the limits of the FOV).
- Launch and forget capability.

3.7 Additional analysis

An additional analysis was performed to evaluate operational effectiveness of multiple release capabilities of OPHER and set suitable/optimal release intervals to avoid that different weapons home to the same target.
The analysis was performed for various combinations of release conditions, target distribution on the ground, stick intervals and number of OPHER systems released in one pass. It has been shown that when attacking various squadron scenarios with a typical low energy mission profile, an optimal stick interval can be defined such that each OPHER system released in this mode (2 up to 4) will hit a different target with a high probability. This probability is not sensitive to targets distribution and release conditions, but it is better for two bombs and decreases for four bomb stick.

Mach No. / Tail position	M=0.6	M=0.9
Folded	0.3	0.3
35° deployment	1.2	1.3
unfolded (70°)	1.3	1.9

Table 1. OPHER stability characteristics

ITEM	PART NUMBER	QUANTITY
MK 82 INERT BOMB BODY	1325-15-008-7475	1
STD LUGS 14" MS 3314	1325-00-116-4452	2
INERT TAIL FUZE M-905	1325-00-988-3798	1
FUZE ADAPTER BOOSTER T46E	1325-00-935-6187	1
DRIVER ASSY ATU 35 BB	1325-00-422-9022	1
FLEXIBLE SHAFT	**NON STANDARD**	1
COUPLER DRIVE ASSY MAU-87 D/B	1325-00-422-9023	1
LANYARD	1325-00-754-6177	2 m
SWIVEL LOOP	1325-15-102-2745	1
ARMING WIRE	837902-1	2
RETAINING CLIP FZU-18	1325-15-109-9419	2
FERRULE	1325-00-028-5817	1
M9 INERT DELAY ELEMENT	1325-00-062-8468	1
FOLDING TAIL ASSEMBLY	1325-15-115-9185	1
FORWARD ADAPTER	1325-15-115-9184	1
AFT RING	1325-15-115-9079	1
DUMMY GUIDANCE SYSTEM	1325-15-115-9178	1
LIVE GUIDANCE SYSTEM	1325-15-115-9082	1

Table 2. OPHER system components

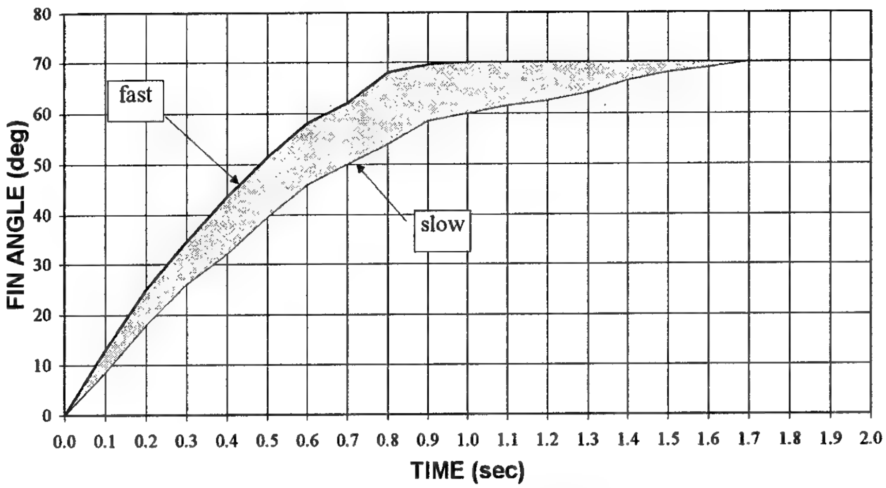


Figure 3. Tail fins opening angle vs. time

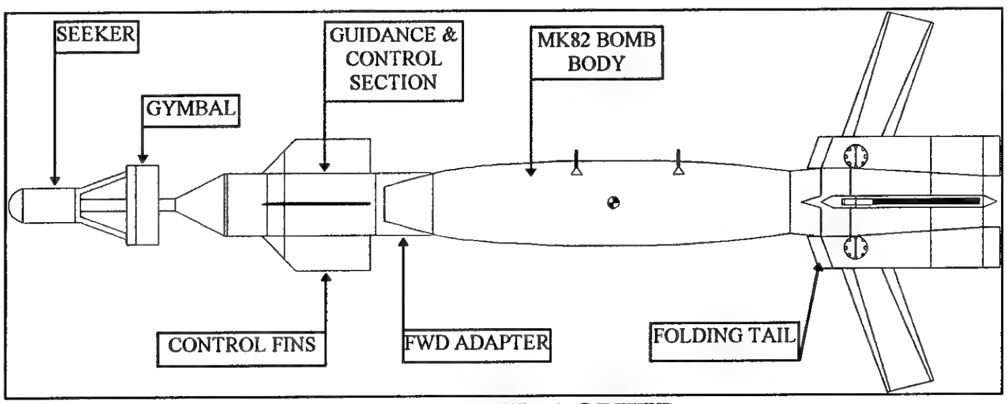


Figure 4a. MK-82 OPHER

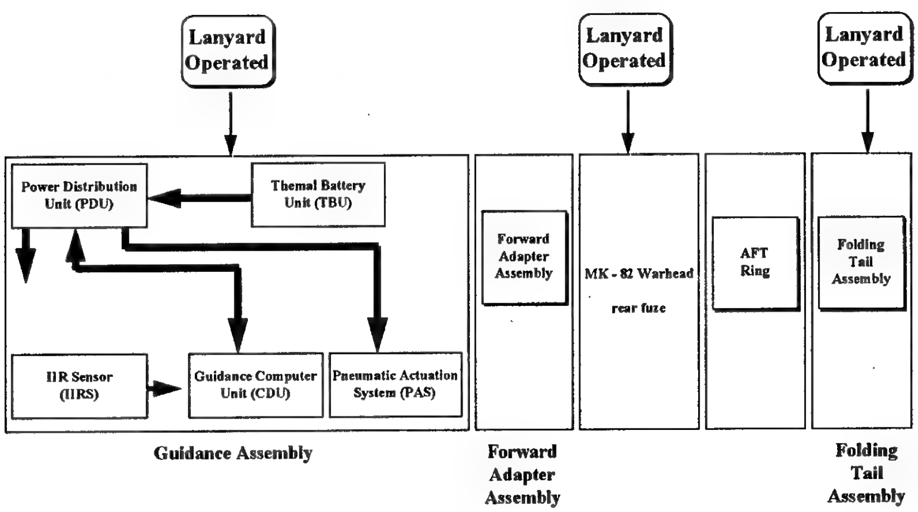


Figure 4b. OPHER system block diagram

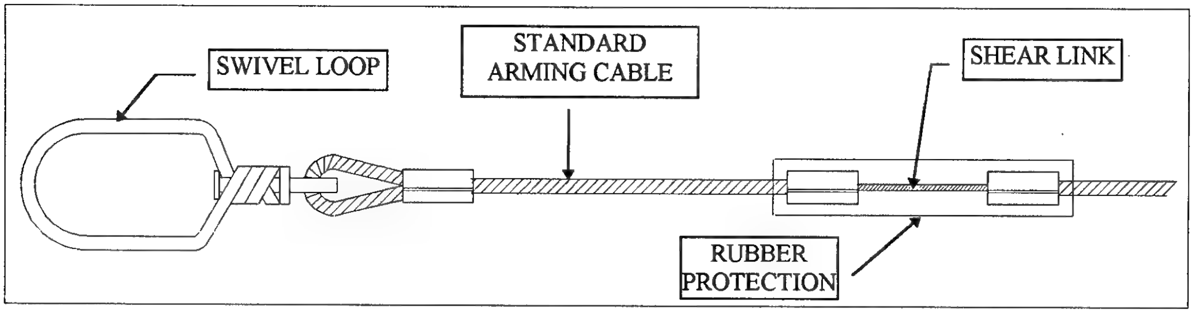


Figure 5. Modified arming cable for TBU activation.

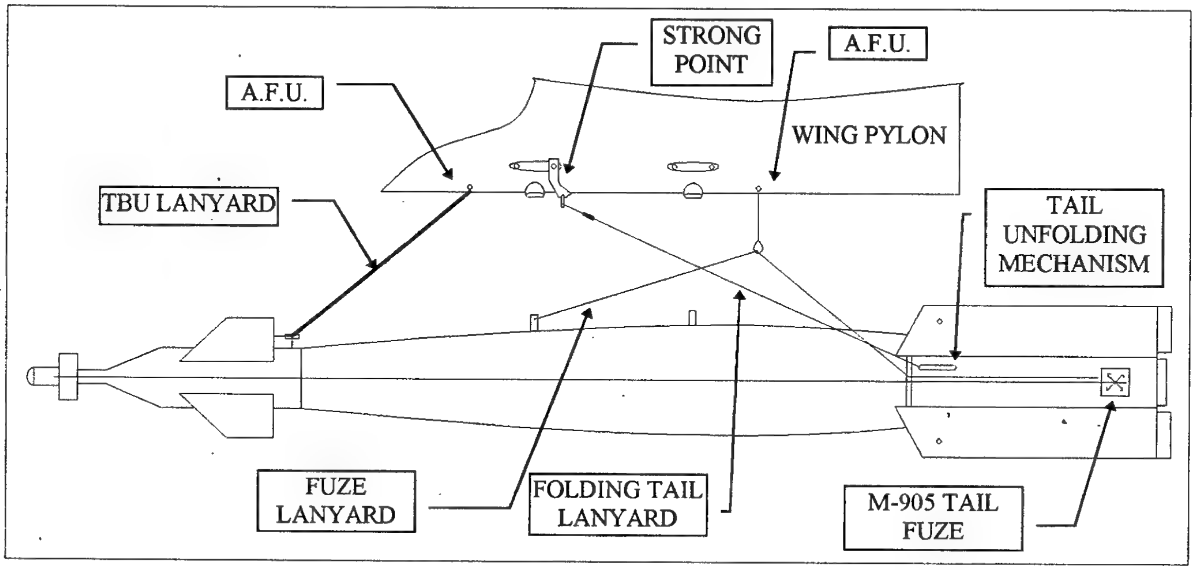


Figure 6. Bomb dressing scheme.

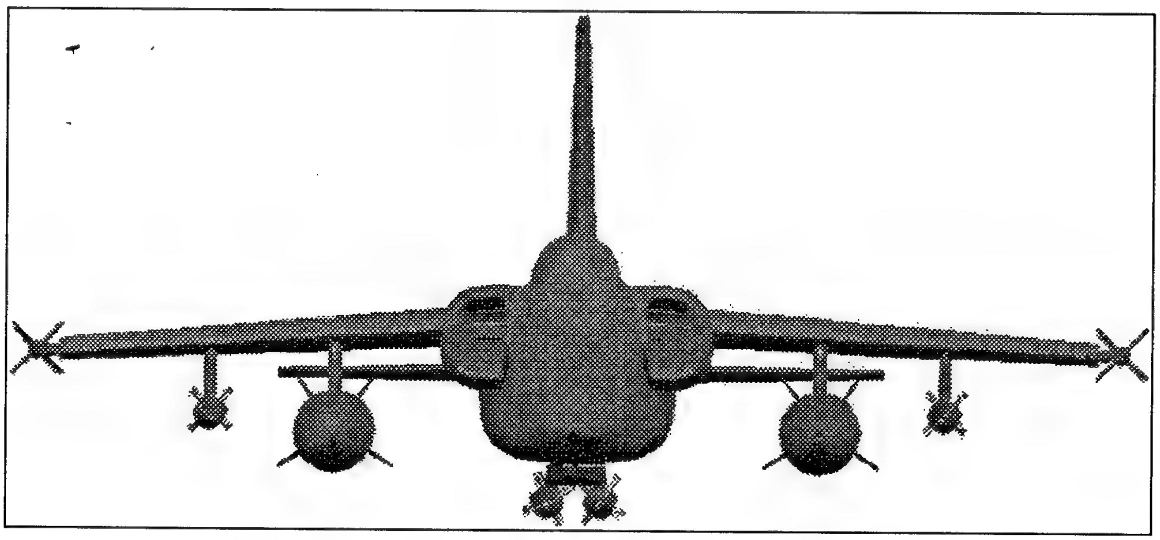


Figure 7. Aircraft configuration.

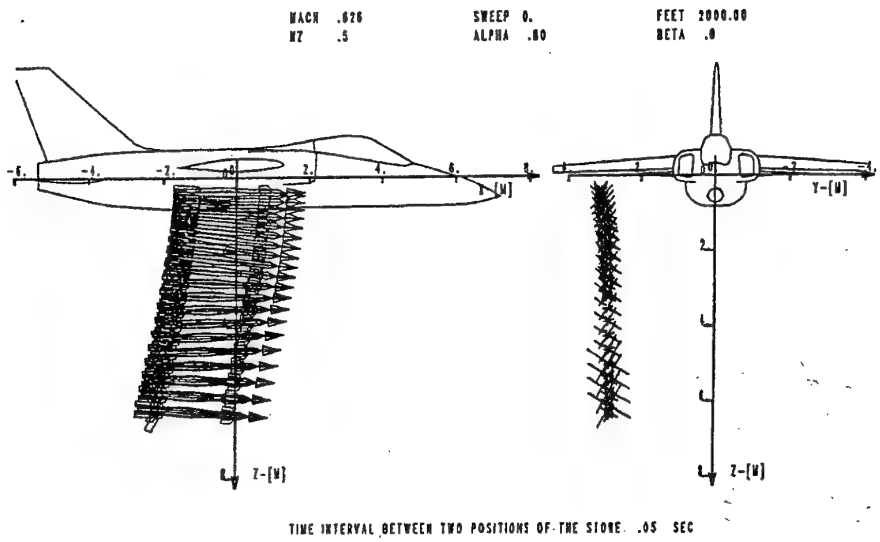


Figure 8. Safe Separation Trajectory Program output.

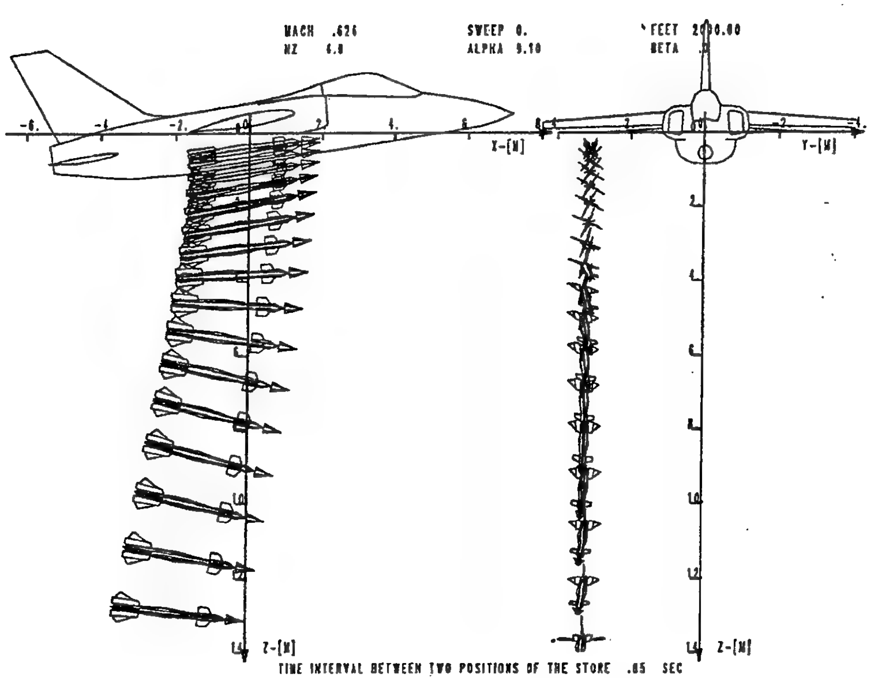


Figure 9. Safe Separation Trajectory Program output.

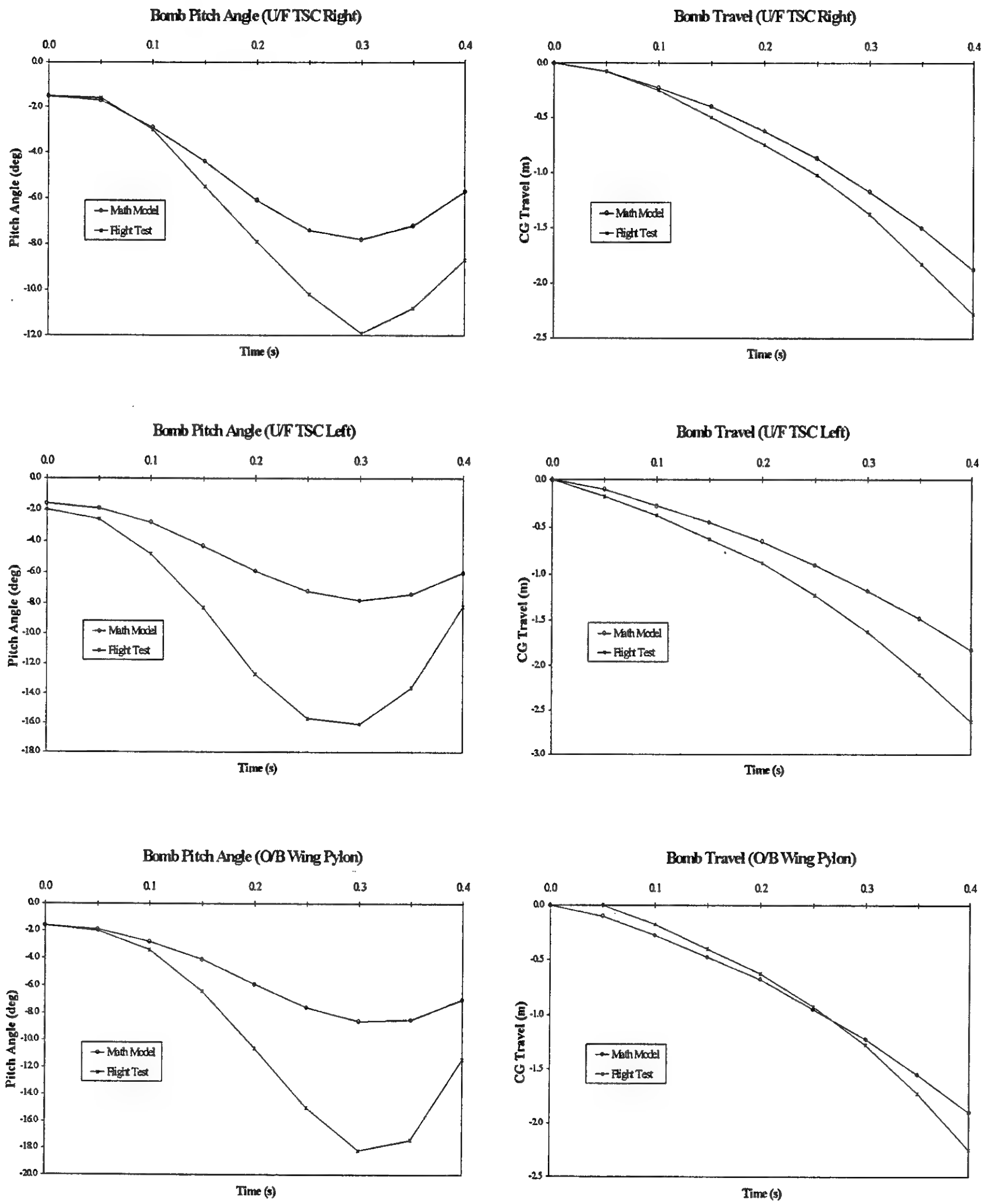


Figure 10. Comparison between mathematical model and flight test results (before math model updating)

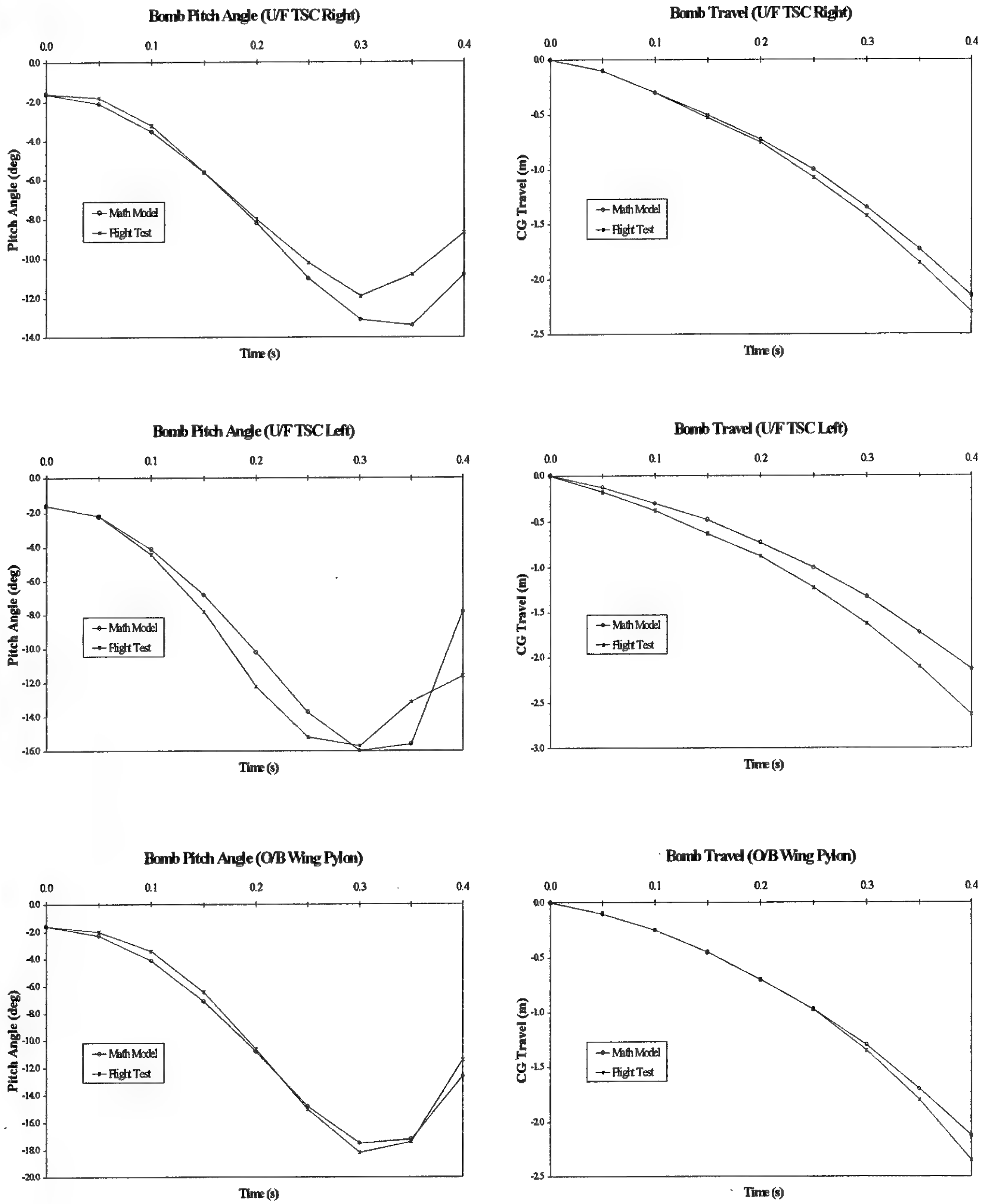


Figure 11. Comparison between mathematical model and flight test results (after math model updating)

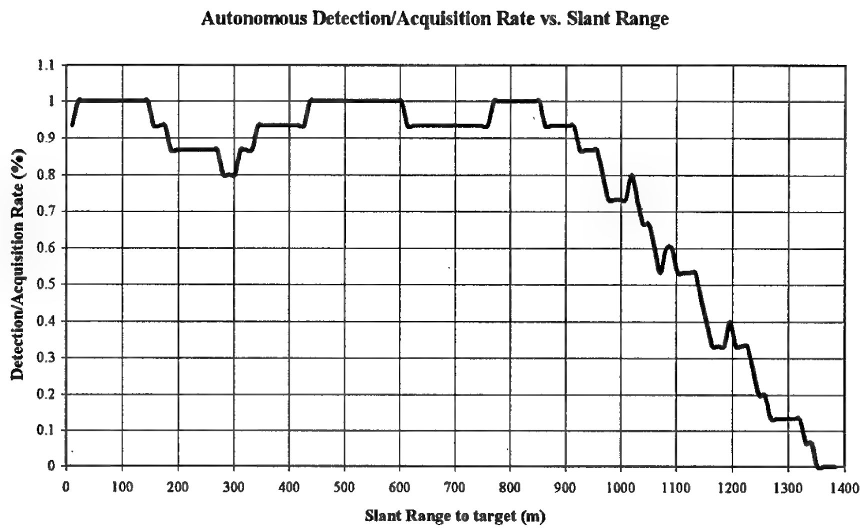


Figure 12. Detection/Acquisition Rate

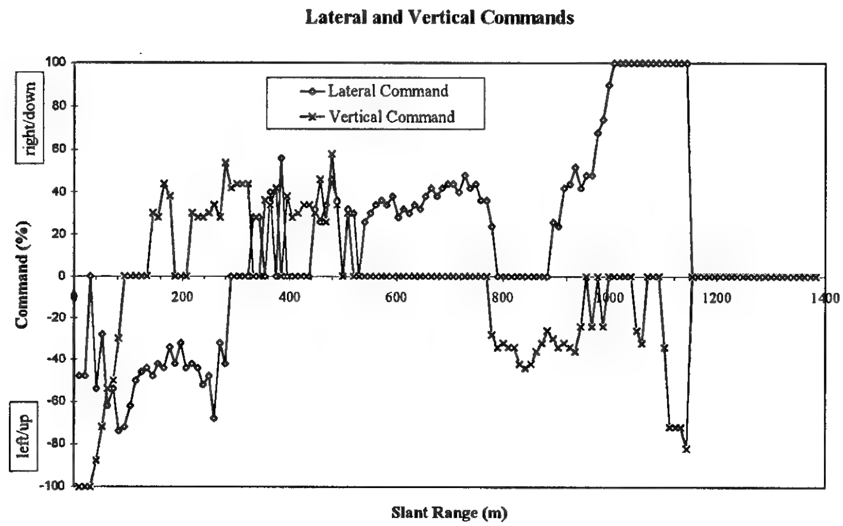


Figure 13. Lateral and Vertical Command Displacements

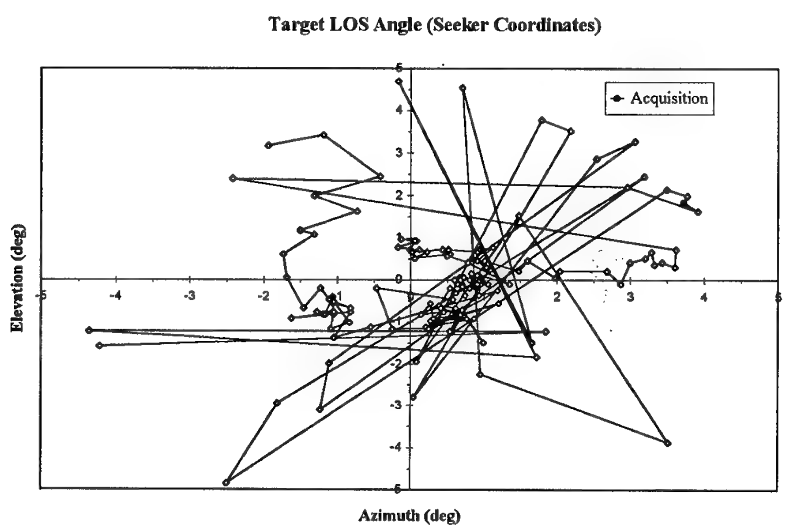
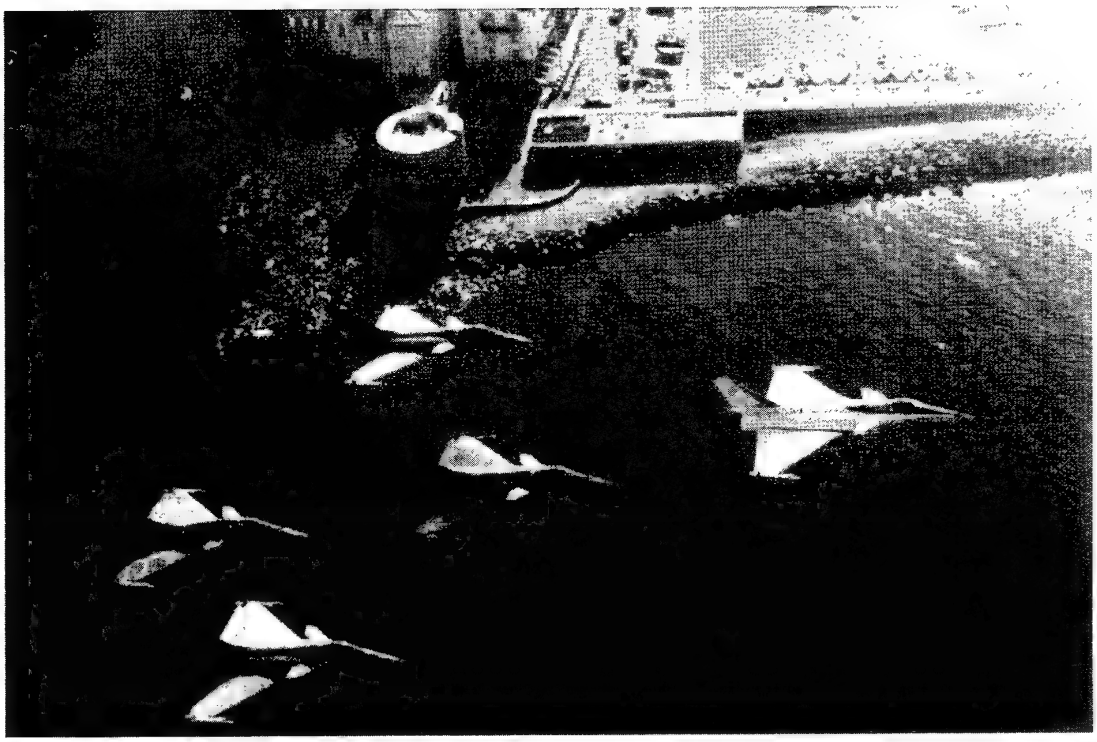


Figure 14. Target Position in Seeker Coordinates

Les essais en Vol du RAFALE

Patrick CASTAGNOS
Responsable des essais en vol RAFALE
Dassault Aviation
BP 28, 13801 Istres Cedex, France

Marc TOURTOULON
Responsable équipe intégrée des essais en vol RAFALE
Centre d'Essais en Vol
13128 Istres Air, France



Résumé :

Les essais en vol du RAFALE ont été l'occasion de relever des défis difficiles, de mettre en oeuvre de nouvelles techniques d'essais, d'adopter de nouveaux schémas d'organisation.

Alors que 5 années se sont écoulées depuis le 1er vol du RAFALE C01 et que les 4 prototypes totalisent plus de 2300 vols, il a paru opportun de se livrer à une comparaison entre les essais en vol tels que nous les avions prévus en 1990 et tels qu'ils se sont réellement déroulés jusqu'à aujourd'hui.

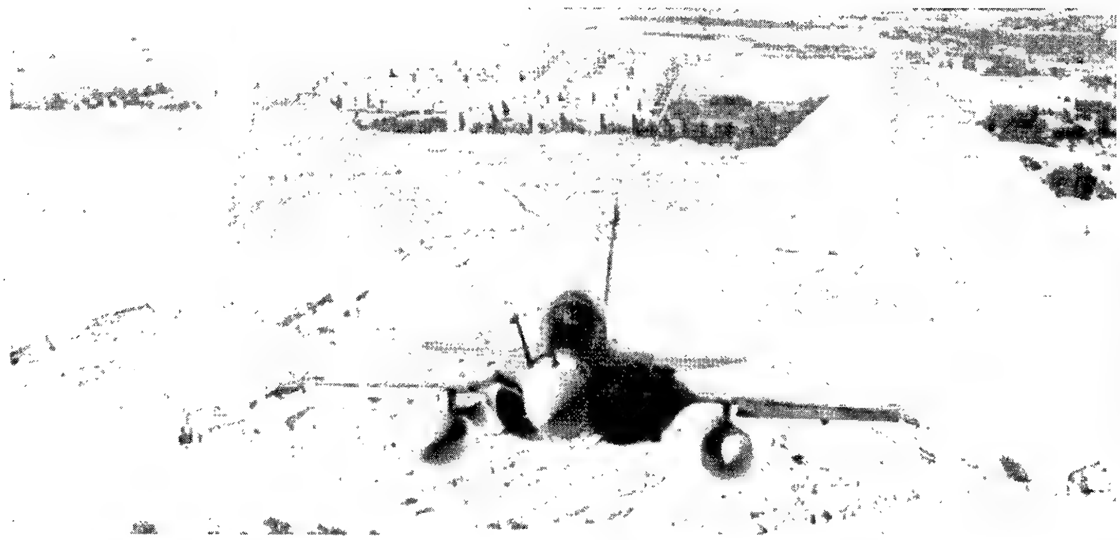
Les deux articles qui suivent effectuent cette analyse. Le premier s'intéresse plus spécialement aux aspects coûts, objectifs généraux du programme et état de la mise au point technique. Le deuxième est plus axé sur les relations état-industrie et sur l'optimisation des compétences et des ressources.

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

Les essais en vol du RAFALE

Regard sur 5 ans d'activité

Patrick CASTAGNOS
Responsable des essais en vol RAFALE
Dassault Aviation



Le 19 mai 1991, Guy Mitaux-Maurouard décollait le RAFALE C01. Ce 1er vol du prototype RAFALE monoplace air fut suivi en décembre de la même année par celui du 1er prototype marine M01 puis, un peu plus tard, par les prototypes biplace B01 et marine M02.

Depuis, les avions ont régulièrement volé ; 85% des essais nécessaires pour la mise au point du système dans le 1er standard sont effectués et l'intérêt marqué par certaines forces aériennes étrangères nous a permis d'aller bien au-delà des limites de notre zone aérienne d'essai et d'agrémenter les dépliants publicitaires de Gizhé, Singapour ou Kuala Lumpur.

Aujourd'hui, même si le ralentissement voulu du programme pour des raisons budgétaires a sensiblement modifié les hypothèses de mise en série, notre impression est que les objectifs techniques, calendaires et financiers du programme ont jusqu'ici été tenus et qu'il n'existe pas de réelle distorsion entre le déroulement des essais en vol tels que nous les avions prévus et tels qu'ils se sont jusqu'à aujourd'hui réellement déroulés.

Au-delà d'un sentiment général, il est toutefois intéressant d'analyser aujourd'hui ces écarts ; ce qui suit en est une première tentative.

Planning général

Le planning officiel de début 1991 prévoyait la mise en vol des 2 premiers prototypes C01 et M01 dans l'année, le vol du B01 début 1993 et le vol du 2ème proto marine M02 mi 1993.

2 campagnes d'essais sur base à terre mi et fin 1992 devaient permettre de poser le RAFALE sur le pont d'un porte avions en avril 1993.

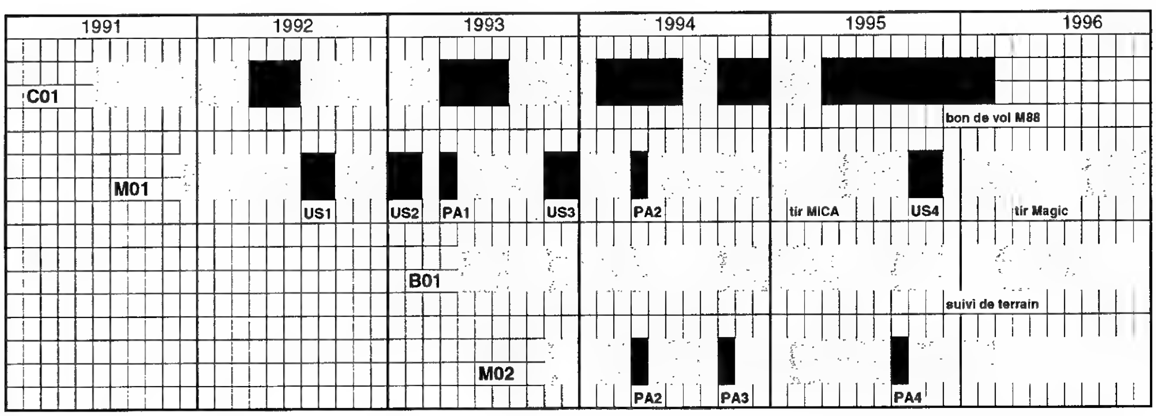
La mise au point de l'ensemble des systèmes avion dans la totalité du domaine de vol nous semblait devoir être acquise après 2 ans de vols, avant que ne nous mobilisent l'ouverture des domaines d'emport avec charges - considérés comme une

formalité suite à l'expérience qu'on en a sur Mirage 2000 -, l'ouverture des domaines de séparation et la mise au point du système.
Du point de vue moteur, le bon de vol était espéré pour fin 95.
Les objectifs de série étaient alors de produire des RAFALE à partir de fin 1996 dans un 1er standard principalement axé sur des missions air-air.

Force est de noter que les premières années d'essais en vol furent très comparables à nos prévisions : malgré une mauvaise surprise sur les générations hydrauliques 350 bars lors des premiers points fixes - quelques minutes de fonctionnement ayant suffi à faire casser en fatigue les tuyauteries aval pompes HP, la situation fut assainie par une action commando et le C01 ne vola qu'avec 2 mois de retard sur le planning objectif. Le M01 vola à la date prévue tandis qu'en 1993 les 2 prototypes suivants volaient 4 mois plus tard que nous ne l'avions imaginé début 1991. Ces légers décalages s'expliquent par la correction de problèmes mis en évidence par les 2 premiers prototypes, quelques retards sur des nouvelles fournitures (sièges, nouveaux composants électroniques) ou par le

Les rendez vous marins furent ponctuellement respectés : une action volontariste, dont un des aiguillons fut de donner tort à ceux qui ne croyaient pas qu'un delta puisse être un excellent avion embarqué, permit d'apponter sur le porte-avions Foch le jour dit. Les rendez-vous suivants furent aussi ponctuels sauf quand la situation internationale appelait les porte-avions à des activités plus opérationnelles et plus lointaines.

L'ouverture du domaine de vol jusqu'à 750 kt/M = 1.8 se fit sans difficulté et la mise au point des systèmes généraux à l'intérieur de ce vaste domaine ne posa pas de gros problème. Remarquons toutefois que, si après 2 ans de vol, les systèmes généraux étaient mis au point à 95%, la finition prit beaucoup plus de temps. C'est le côté pervers du "tout numérique" ; la moindre modification de logique dans un système risquant soit de dégrader le niveau de sécurité du système considéré, soit d'avoir des effets secondaires sur d'autres systèmes, toute évolution nécessite de longs mois d'instruction et de délicates opérations de coordination entre les industriels. Alors qu'il y a une dizaine d'année, nous attendions avec impatience que des calculateurs numériques



PLANNING DES 4 PROTOTYPES

déménagement de l'atelier de fabrication prototype initialement situé au sein du bureau d'études vers l'usine de production. Eu égard à l'importance du changement, cette mesure de rationalisation industrielle n'ayant, en fin de compte, que peu altéré les opérations de fabrication.

embarqués nous permettent à loisir de jouer avec les logiques et d'optimiser les systèmes en un tournemain, nous pensons parfois aujourd'hui avec nostalgie à l'époque où un fer à souder et quelques résistances permettaient, dans la soirée, de

modifier une loi de freinage sans craindre que cela n'influe sur la séquence de sortie du train.
La mise au point du système d'avionique et d'armements s'est initialement déroulée au rythme prévu puis s'est progressivement ralentie dans un contexte où les délais doivent s'effacer devant l'économie.

Toutefois, on peut aujourd'hui considérer qu'une bonne partie du chemin est déjà parcourue, notamment dans la mise au point du 1er standard opérationnel. En particulier, des tirs Magic et Mica sur cibles ont permis de valider les conduites de tir tandis que des essais de suivi de terrain nous ont pleinement rassurés sur l'architecture du système et la précision de localisation de l'avion.
Dans le contexte budgétaire et politique précédemment souligné, le début de la série a été repoussé de 2 ans soit 2ème semestre 98.

Volume des essais en vol

Dès le début du programme, quand il fut nécessaire de déterminer le nombre de prototypes nécessaires et leur date de disponibilité pour assurer le développement, des discussions âpres s'engagèrent. Nombre d'éléments incitaient à prévoir large pour ne pas se laisser surprendre par les difficultés de la tâche :

- développement simultané d'un monoplace air, d'un biplace air et d'un monoplace embarqué sur porte-avions,

- innovations nombreuses dans la définition de la cellule et des systèmes généraux,

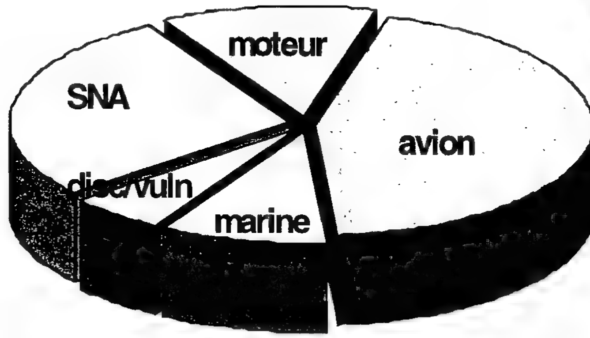
- mise en oeuvre de technologies de furtivité,

- nécessité de traiter très tôt les problèmes de vulnérabilité électromagnétique,

- système d'armes ambitieux dès le 1er standard.

A l'opposé, les contraintes budgétaires exigeaient que le nombre de mois d'essais en vol soit réduit au strict nécessaire.
Une attitude particulièrement volontariste permit de maintenir notre prévision à un volume comparable à ce que le Mirage 2000 avait nécessité lors de ses essais initiaux : environ 190 mois x avions de développement entre le 1er vol du 1er prototype et le 1er vol de l'avion de série.

Un gain de productivité particulier était attendu des essais de mise au point avion (cellule, systèmes généraux, emports, séparations) dont le volume était, par rapport au Mirage 2000, divisé par 2.



Répartition des essais du 1er standard

Aujourd'hui, ce pari est en passe d'être gagné : alors que plus des trois quarts de ce volume d'essai a été réalisé, notre prévision recalée montre que :

- le nombre total de mois d'essai sera sensiblement égal à la prévision de 1991,

- les essais de mise au point cellule auront été légèrement plus consommateurs de temps (les gains de productivité entre le Mirage 2000 et le RAFALE auront quand même été de 40% - pour 50% espérés -),

- la mise au point moteur est restée à l'intérieur du quota alloué,

- le bon déroulement des essais spécifiques Marine a permis quelques gains,

- de nouvelles méthodes mises en oeuvre lors des essais de vulnérabilité et de discrétion ont permis des gains appréciables (40% du temps prévu a été économisé),

- la mise au point du système d'avionique et d'armements sera réalisée dans le temps prévu,

Deux unités permettent d'évaluer une activité d'essais en vol : le nombre de mois d'essais et le nombre de vols.
Si le nombre de mois d'activité - au sol ou en vol - des avions de développement est une donnée essentielle car directement corrélée au coût, le nombre de vols n'est pas moins intéressant : c'est un indicateur de la maturité de l'avion et de la fiabilité que l'on pourra espérer avec les avions de série. Début 1991 nous évaluions à 1500 vols,

l'expérience, nécessaire à la maîtrise des risques, dont nous disposerions au moment de la sortie en série. Calculé à partir du nombre de mois d'essais prévus et des cadences de vol "classiques" suivant les types d'essais, ce volume de vols nous semblait un plancher sous lequel il ne fallait pas tomber. Aujourd'hui plus de 2300 vols ont été réalisés par les 4 prototypes, sans compter les 867 vols du démonstrateur RAFALE A. Même si certains vols réalisés à partir du porte-avions Foch (catapultage - vidange - appontage) ne constituent pas des records d'autonomie en l'air, nous pouvons mettre en avant une expérience solide et faire état d'une excellente fiabilité. En corrolaire de l'activité totale, quelques chiffres peuvent être soulignés :

- pendant le mois d'octobre 1994, le M02 a fait 52 vols d'essais dont 25 depuis le porte-avions,

- durant la dernière campagne d'essais sur base à terre, en 6 semaines d'essais, le M01 a réalisé 57 catapultages et plus de 120 arrêts par brin dans 8 configurations d'emport différentes,

- au cours des vols de convoyage vers les Salons aéronautiques de Dubaï et Singapour, des étapes de plus de 7 h ont été faites avec ravitaillement en vol.

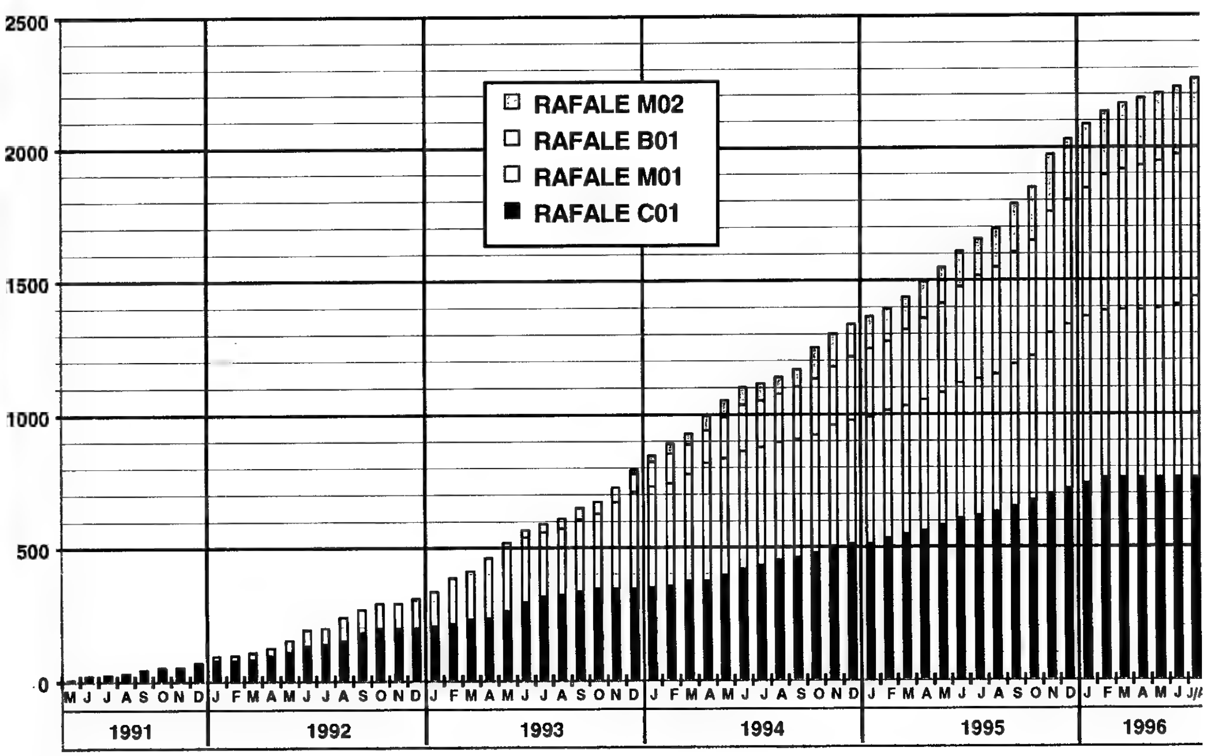
Composition de l'équipe d'essais

Rentrer dans le détail des métiers et de leur évolution ces dernières années nous emmènerait loin et serait d'un intérêt réduit tant l'organisation est liée à la culture de l'entreprise. Certaines tendances méritent toutefois d'être soulignées. Bien qu'entrevoyant l'organisation dans la continuité des programmes précédents - une forte proportion de l'équipe d'essai en vol du RAFALE ayant précédemment travaillé aux essais en vol du Mirage 2000 ou du démonstrateur RAFALE A -, il fut décidé en 1990,

. de mettre en commun les personnels travaillant sur les bancs d'intégration et ceux affectés à la mise en oeuvre des systèmes sur avion ;

. d'augmenter, dans les équipes de mise en oeuvre avion, la part des techniciens dits "systèmes" donc d'une culture plus électronique/automatique/informatique que mécanique ;

. de renforcer le département des ingénieurs d'essais spécialistes - destinés à suivre les problèmes de leur compétence sur les différents programmes - afin de traiter correctement les



NOMBRE DE VOLS EFFECTUES PAR LES 4 PROTOTYPES

technologies les plus pointues. A cet égard, certains pensaient alors que s'éteignait l'ère de l'ingénieur d'essai généraliste, historiquement meneur des équipes d'essais, capable de s'occuper de tous les thèmes d'essais en vol ;

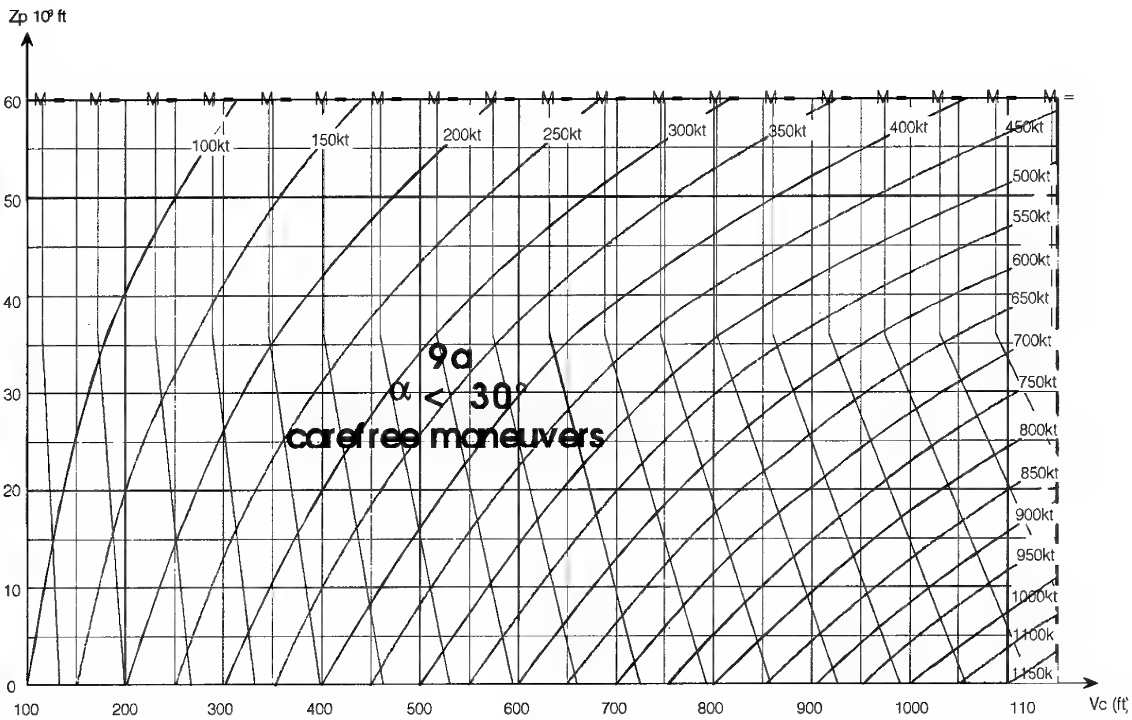
d'intégrer à l'équipe d'essai un contrôle budgétaire local. Il était clair, dès le début, que les aspects économiques seraient un point focal et qu'il faudrait veiller avec acuité à respecter les allocations budgétaires.

5 ans d'expérience prouvent bien que la mise en oeuvre d'un avion aux systèmes totalement intégrés est, en essais, plus compliquée que pour les avions de génération précédente. A titre d'exemple, un essai de manoeuvre train au sol ne nécessitait que de mettre l'avion sur vérin et de l'alimenter en hydraulique ; un bon chronographe et l'observation des lampes en cabine faisaient le reste - Aujourd'hui un tel essai sera incomplet - et parfois non faisable - si les calculateurs de mission et les visualisations ne sont pas mises en route et si on n'observe pas avec des "espions de bus" que

les 2 voies du calculateur numérique d'atterrisseur commandent des ordres simultanés et cohérents - Les équipes de mise en oeuvre des prototypes ont donc vu leur niveau technique s'accroître considérablement avec parfois pour corollaire une "spécialisation excessive". Il a fallu batailler parfois pour ne pas voir émerger des "Monsieur mise en oeuvre du carburant", "Monsieur mise en oeuvre des visualisations"... Notons que la tâche est dure parfois pour nos ingénieurs de piste - chefs des équipes de mise en oeuvre des prototypes - qui doivent traiter avec la même dextérité les problèmes mécaniques et les subtilités des logiques internes des calculateurs.
Toujours au chapitre de la maîtrise de la complexité, nous avons réussi à ce que les ingénieurs d'essais programme restent des généralistes capables d'enchaîner des essais aussi différents que des vols d'ouverture de domaine et des essais d'intégration de contre-mesures. Cette capacité nous semble essentielle pour maîtriser la mise au point d'un avion et opérer les bons arbitrages.
Le contrôle de gestion n'a pas - pas seulement ! - eu pour but de fournir des tableaux de bord de synthèse à notre direction de programme mais de veiller sur place, et avec un temps de réaction très court, à ce que les courbes de dépenses ne s'infléchissent pas dans le mauvais sens - Dans ce domaine, les méthodes mises en oeuvre sur RAFALE se sont généralisées à tous les programmes, ce qui tend à en prouver l'efficacité.

Domaine de vol

Traditionnellement, l'ouverture des domaines de vol est effectuée avec célérité sur les avions Dassault. Le RAFALE n'a pas failli puisque, dès son 1er vol, le RAFALE C01 évoluait dans le domaine 450 kt/M = 1.2/4 g.
8 g étaient obtenus au 5ème vol et M = 1.6 au 27ème vol. Le domaine de vol a donc été ouvert jusqu'à 750 kt/M = 1.8/9 g et 30° d'incidence sur les 3 versions du RAFALE sans rencontrer de problème notable sur la structure, les commandes de vol, ni sur l'ensemble des systèmes.
Du côté des basses vitesses, la limite est 100 kt mais 80 kt est parfois pratiqué lors des démonstrations en vol par des pilotes désireux de mettre en valeur les qualités de l'avion. Un minimum de 15 kt a été pratiqué dans un exercice de combat contre un Mirage 2000 par un pilote vindicatif ; c'était donc un essai avec un peu d'avance sur une campagne de vols à grande incidence que, vus les risques inhérents à ce type d'évolutions, nous n'avons prévue que lorsque nous considèrerons qu'un prototype est "surabondant".
D'une manière générale, l'ouverture des domaines de vol se fit donc sans heurts et les méthodes mises en oeuvre (modélisations, simulations, mode de progression) s'avérèrent sures et efficaces. Le seul point qui mérite réflexion est la circonspection que



DOMAINE DE VOL OUVERT

nous eûmes à déployer à l'origine du programme pour ouvrir le domaine à basse altitude grande vitesse ; celui-ci est significatif des problèmes que posent les systèmes intégrés. A partir de divers capteurs, l'anémo-baro-clinométrie de l'avion est calculée par les calculateurs des commandes de vol qui l'utilisent à leur profit pour adapter les différentes lois de pilotage aux conditions de vol et distribuent ces données (Mach, vitesse, incidence...) à l'ensemble des systèmes de l'avion y compris les moteurs. Lorsqu'une cascade de pannes fait totalement perdre les sources anémo-baro-clinométriques, chaque système se replie sur un fonctionnement dégradé, qui dans la 1ère phase du développement impliquait certaines contraintes. Ainsi, en supersonique basse altitude les commandes de vol exigeaient-elles que, en panne totale d'anémométrie, le pilote rejoigne le subsonique moyenne altitude pour y sélectionner un mode secours en suivant un profil de vol particulier (montée supersonique puis décélération iso altitude). Parallèlement les moteurs, en l'absence de conditions de vol de référence, interdisaient l'usage de la post-combustion. Les études de sécurité préalables au 1er vol du RAFALE C01 mirent en évidence un hiatus : dans le coin du domaine situé en supersonique en dessous de 10000 ft - dénommé "Triangle des Bermudes" - la poussée des moteurs en plein gaz sec ne permettait pas de monter iso-Mach. Comme l'amélioration de ces fonctionnements dégradés n'était possible qu'après être allé identifier finement les coefficients aérodynamiques et les modes souples de l'avion, l'ouverture du domaine de vol se fit néanmoins. Nous limitâmes toutefois au strict nécessaire les incursions dans le "triangle des Bermudes" et les vols correspondants ne se firent qu'avec une vigilance accrue sur le fonctionnement de l'anémométrie et après que les pilotes aient répété de multiples fois au simulateur une procédure à appliquer en cas de panne. Grâce à cela, aujourd'hui, 750 kt est ouvert à toute altitude ; depuis, en cas de panne totale anémo la post-combustion reste disponible et il est seulement demandé au pilote de rejoindre le subsonique en palier.

Qualités de vol

Le système de commandes de vol est numérique 3 chaînes avec secours électrique analogique. Un module de surveillance veille à la cohérence du comportement de l'avion et ferait commuter du numérique vers l'analogique au cas où une évolution anormale de l'avion serait détectée. Cette architecture a déjà été éprouvée sur le RAFALE A de même que la méthode de validation du logiciel qui inclut un cycle final de plusieurs centaines d'heures en boucle fermée au Banc de Simulation Global.

Le travail des essais en vol consiste pour une part importante à recaler en vol les modèles

aérodynamiques afin d'optimiser les réglages des commandes de vol. Pour cela, on dispose à bord de l'avion d'un boîtier (Boîtier Programme Multifonction BPM) qui, via les gouvernes, génère des stimuli. L'enregistrement des réactions de l'avion à ces sollicitations permet de restituer les coefficients aérodynamiques. Le volume d'essai nécessaire pour assurer ce recalage fut dans l'ordre de grandeur prévu et l'ampleur des corrections en accord avec la confiance que l'on accordait aux modèles : le subsonique et le supersonique étaient parfaitement modélisés ; le transsonique nécessita de nombreuses mesures, ce d'autant plus que les contraintes de l'anémométrie actuelle - pas de perchette de nez, mesures brutes dépendant de multiples paramètres - ne facilitent pas la tâche.

Parallèlement à ce travail très méthodique, les essais en vol ont pour but de vérifier que les performances requises (incidence, facteur de charge maximum, taux de roulis ...) sont atteints, que l'avion est bien protégé contre toute surcharge structurale et toute perte de contrôle, que le pilotage de base permet au pilote de faire évoluer l'avion selon son gré et sans y consacrer une attention excessive, que les modes de pilotage automatique permettent de le décharger totalement du souci de conduite de l'avion.

Dans l'ensemble de ce travail, le processus utilisé nous a semblé bien maîtrisé :

- les essais en vol se sont situés dans la stricte continuité du travail réalisé en commun par les équipes de définition et les équipes d'essais sur le simulateur global. Nous n'avons donc jamais été étonnés par ce que nous trouvions en vol ; nous ne faisions que travailler avec un simulateur plus représentatif que lors de l'étape précédente,

- l'architecture s'est avérée robuste et la qualité du logiciel n'a jamais été mise en défaut. Le module de surveillance nous a fait automatiquement passer en analogique à 4 reprises mais à chaque fois parce que les seuils de surveillance étaient trop étroits par rapport au comportement réel de l'avion. Depuis plus de 3 ans, aucun déclenchement du module de surveillance n'est intervenu et, dans l'avion de série, nous pourrons assurer qu'il n'en existera pas,

- nous mettons en vol, ce mois-ci, la version 4 du système de commande de vol. Cette version dite "de série" permet de voler dans l'ensemble du domaine, avec les performances exigées et dans toutes les configurations d'emports que nous avons identifiées. Les évolutions par rapport à la version précédente, en vol depuis 1 an, en sont peu nombreuses dans la mesure où tant les modes de base que les modes automatiques sont actuellement jugés d'une excellente qualité.

Avoir des lois de commandes de vol bien optimisées pour protéger la structure, obtenir les facteurs de charge, incidences, taux de roulis requis et assurer le pilote qu'il ne risque pas de perte de contrôle quelle que soit la manoeuvre apparaît donc comme issue logique de la méthode de travail. Les critères qu'il faut satisfaire pour que le pilote "sente bien" son avion sont moins rigoureux.

A cet égard, 2 thèmes de mise au point furent plus difficiles qu'on ne s'y attendait : le mini-manche latéral et le mode automatique de tenue de vitesse train sorti. Dans les 2 cas, les sensations pilotes sont essentielles et les simulateurs, malgré tous les raffinements qu'on y a intégrés, ne permettent pas d'y finaliser les réglages.

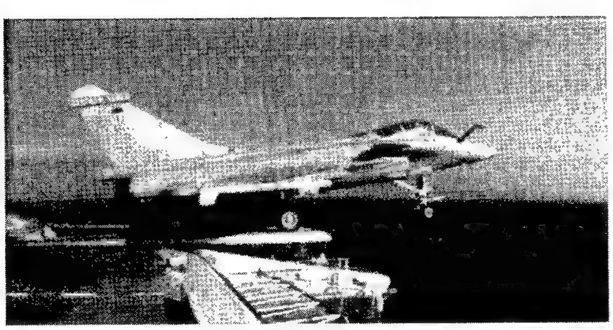
Dans les phases classiques du pilotage (autour du neutre, sur la butée) le mini-manche latéral fut initialement apprécié mais au fur et à mesure que les pilotes se succédèrent, que l'avion fut essayé dans des conditions plus opérationnelles - vol en formation, ravitaillement en vol -, il fut évident que la précision des commandes n'était pas au niveau

requis. Par le BPM, nous nous donnâmes la capacité d'essayer en vol de nouveaux Amédées (lois de commandes non linéaires), de nouveaux filtrages de la commande mais il fut rapidement déterminé que des modifications mécaniques du manche s'imposaient, en particulier pour obtenir une homogénéité de comportement sur le roulis et le tangage ; par de simples modifications de logiciel, toute amélioration sur un axe avait pour contrepartie de rendre l'autre axe trop sensible. Une augmentation de 44% du débattement manche à cabrer - ce qui ne fait jamais que 3.5 mm en plus - et de nouvelles lois d'effort en profondeur et gauchissement permirent d'aboutir à un "bon manche" qui devint excellent lorsque des raffinements tels que des filtres à avance de phase furent implantés dans le logiciel. La leçon à en tirer restera toutefois qu'il convient dès le début du développement de se donner la possibilité dans le logiciel d'essayer en vol de multiples lois, temporisations mais que, de la même façon une palette d'aménagements mécaniques doit être disponible. Initialement, se doter de ces capacités paraît toujours une politique chère et source de nombreux vol, d'avis pilotes multiples et difficiles à synthétiser.
Dans les faits il s'avère que seul le vol permettra la mise au point et que l'impératif d'excellence dans le domaine de la pilotabilité imposera bon gré mal gré la mise en oeuvre des moyens précédents.
Le mode "couplage manette train sorti" a pour objectif de tenir précisément la vitesse en approche afin, en particulier, de minimiser la dispersion de vitesse d'entrée brin sur porte-avions. Dès sa première version, ce mode s'avéra très efficace avec une tenue à $\pm$ 2kt dans des conditions représentatives d'emploi sur porte-avions. Les pilotes les plus enthousiastes utilisèrent donc ce mode systématiquement et sans état d'âme. Toutefois arrivèrent sur le programme de nouveaux pilotes moins confiants dans les capacités des asservissements numériques et qui regrettèrent de ne pas retrouver sur RAFALE les sensations qu'ils avaient sur les avions de la génération précédente : en pilotage manuel, leur tendance aurait été de commander aux moteurs des réactions plus vives et de moindre amplitude ; en conséquence la vigilance qu'ils devaient maintenir sur la vitesse faisait perdre une partie de l'intérêt de ce mode automatique. Toujours grâce au BPM, on se donna le choix de plusieurs types de réglages du mode (constante de temps, gain d'asservissement) et l'optimum fut déterminé en vol : la performance
s'en trouva légèrement dégradée avec une tenue à $\pm$ 3 kt mais les réactions de l'avion apparurent plus naturelles et satisfaisantes pour tous. Comme précédemment la leçon à en tirer est que, sur tout mode pour lequel la performance n'est pas le seul critère tandis que la sensation pilote est un paramètre important, il convient de se donner, dans le logiciel, le choix de divers réglages à essayer en vol.

Spécificités Marine

Finalisée en 1990, la logique de développement des essais Marine faisait apparaître 4 campagnes sur base à terre et 3 campagnes sur porte-avions pour qualifier l'avion dans l'état du 1er standard. L'enchaînement des essais était le suivant :

- une campagne sur bases à terre - Lakehurst et Patuxent River - en configuration de base (2 Magic) pour identifier le comportement de l'avion au catapultage et à l'appontage,
- une deuxième campagne quelques mois plus tard dans la même configuration afin de valider les corrections des faiblesses éventuellement mises en évidence durant la 1ère campagne,
- une première campagne sur porte-avions Foch,
- une deuxième campagne sur Foch avec 2 avions dont un équipé de radar et de contre-mesures,
- une campagne d'essais sur base à terre pour catapulter et apponter un avion équipé des charges du 1er standard : réservoirs largables et missiles air-air,
- une campagne sur porte-avions dans les configurations du 1er standard,
- une campagne "charges lourdes" sur base à terre destinée à catapulter et apponter dans les conditions extrêmes de masse, centrage, chargement de chaque point d'emport, dissymétrie afin de valider la structure de l'avion avant passage en série.



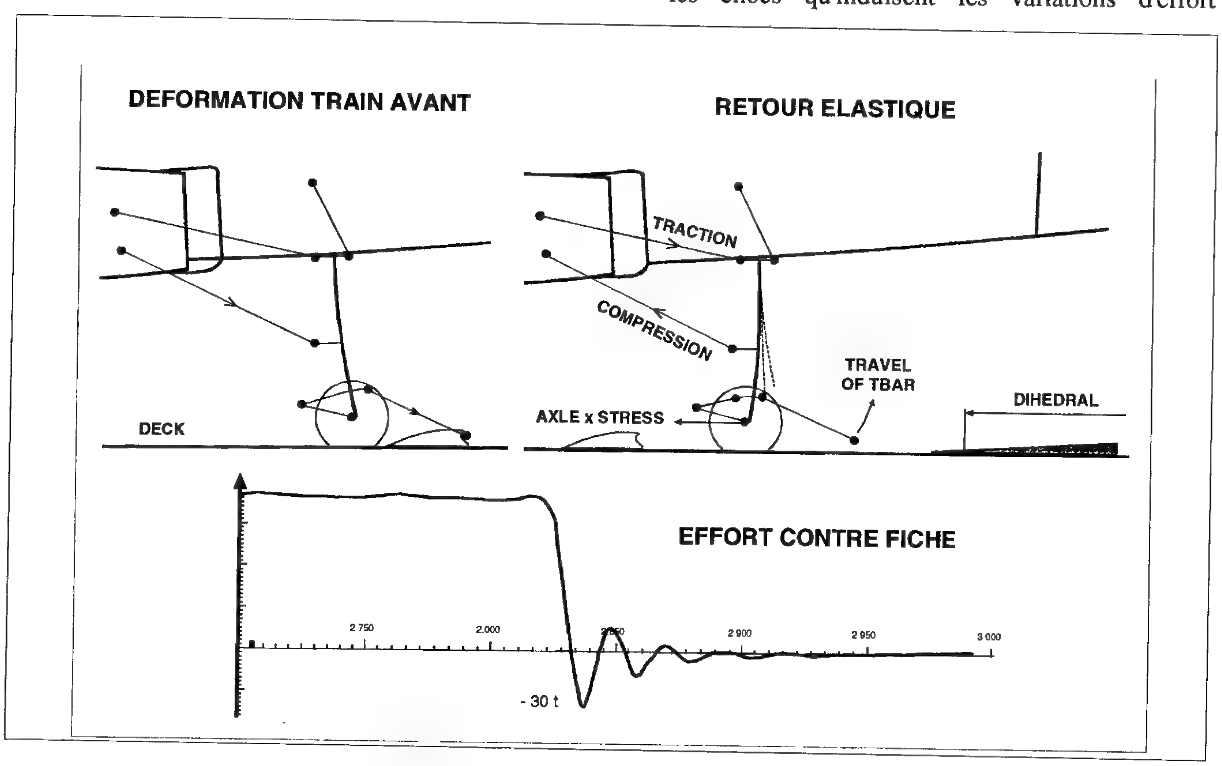
A l'époque, les points durs que nous imaginions concernaient principalement :

- la mise au point du mode automatique des commandes de vol qui assure la mise en vol au catapultage - Plusieurs éléments concouraient à cette inquiétude : la mise en vol en bout de pont nécessite sur un delta une prise d'incidence énergique - pour avoir rapidement de la portance - et bien maîtrisée pour ne pas excéder une incidence au-delà de laquelle la traînée serait trop élevée ; l'utilisation d'un dièdre ou d'un dispositif de restitution d'énergie du train pour obtenir une prise d'assiette rapide étaient aussi des nouveautés à défricher,

- les risques de désorientation spatiale au catapultage. Pour la 1ère fois sur un avion embarqué, le pilote est dans un siège incliné de 29°, soumis à une forte accélération (5.5 g) immédiatement suivie d'une vitesse de tangage importante (30°/s). Le risque que le pilote en soit perturbé apparaissait réel.

- le vérin de crosse dont le réglage risquait d'être pointu vu la forme du fuselage arrière et l'assiette de l'avion à l'appontage.

En revanche, les problèmes de tenue structurale ne nous apparaissaient pas comme particulièrement difficiles tant les méthodes (modélisation ELFINI, mesures sur avion, recalage de modèle) que nous utilisons quotidiennement sont fiables et maîtrisées.
Le 10 juillet 1992, 7 mois après son 1er vol le RAFALE M01 était sur la catapulte TC13-2 de Lakehurst pour y débuter une progression qui, en 4 essais, devait permettre d'atteindre 3 g d'accélération (soit environ 45 tonnes de traction catapulte). Nous avions ensuite prévu une longue série d'essais destinés à vérifier l'efficacité du dièdre et celle du train à restitution d'énergie ; puis nous progresserions lentement en vitesse de tangage et incidence en sortie de catapulte. Ensuite nous reprendrions la progression en accélération jusqu'à démontrer 5.5 g.
Le désenchantement fut rapide : dès le 1er catapultage, nous mesurâmes des efforts nettement plus importants que prévus dans le train avant ; ralentissant le rythme de progression nous enregistrions dès les 1ers essais, des accélérations au niveau du train avant bien supérieures à l'étendue de mesure garantie des capteurs. Divers éléments - biellettes, ressorts - s'avéraient sous dimensionnés. Nous avions largement sous-estimé les chocs qu'induisent les variations d'effort



CHOC AU CATAPULTAGE

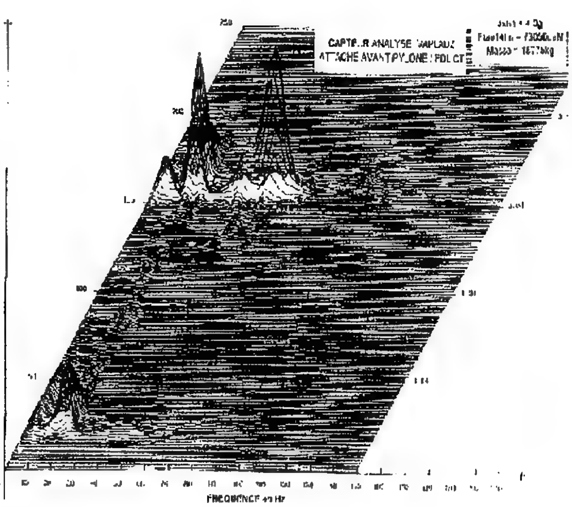
rapides - jusqu'à 90 tonnes en 10 ms - inhérentes au catapultage en tirant directement l'avion par le train (et non au travers d'élingues).
Divers bricolages opérés sur place nous permirent d'accélérer l'avion jusqu'à 3.2 g mais il faudrait attendre d'avoir sensiblement modifié le train avant pour reprendre la progression en accélération longitudinale. Sur les autres aspects en revanche, on constata que tremplin et train à restitution d'énergie avaient les effets attendus ; nos spécialistes de commandes de vol ne nous déçurent pas non plus : la concordance entre le comportement au simulateur global et l'avion en sortie de catapulte était totale.

L'avion n'était pas revenu des Etats-Unis que déjà, 3 actions d'envergure étaient lancées :

- la première consistait en diverses modifications du train avant allant du renforcement d'éléments existants à l'adjonction de nouveaux dispositifs,

- une modélisation était mise en place pour simuler les chocs d'un catapultage et justifier la nouvelle définition du train avant,

- un nouveau moyen d'essai était développé au Centre d'Essais Aéronautique de Toulouse afin de soumettre un train avant à des chocs de l'ampleur et de la brutalité rencontrées sur catapulte.



ANALYSE FREQUENTIELLE DU CHOC

La mobilisation des équipes fut exemplaire et 4 mois plus tard, le RAFALE M01 avec un train avant tout neuf était à nouveau sur la catapulte TC13-2. La progression put reprendre et on démontra rapidement 5.5g d'accélération ce qui permit :

- de qualifier tous les équipements de l'avion,

- de justifier la structure,

- de confirmer toutes les modélisations "commandes de vol",

- de se rassurer sur l'aptitude d'un pilote à supporter le profil particulier du catapultage de RAFALE : ce que nous confirmeraient plus tard des catapultages de nuit sur porte-avions, non seulement le pilote n'est pas désorienté mais l'installation en cabine, la clarté des figurations et la netteté avec laquelle l'avion est mis en l'air par les commandes de vol concourent à mettre le pilote dans des conditions de lucidité sans précédent.

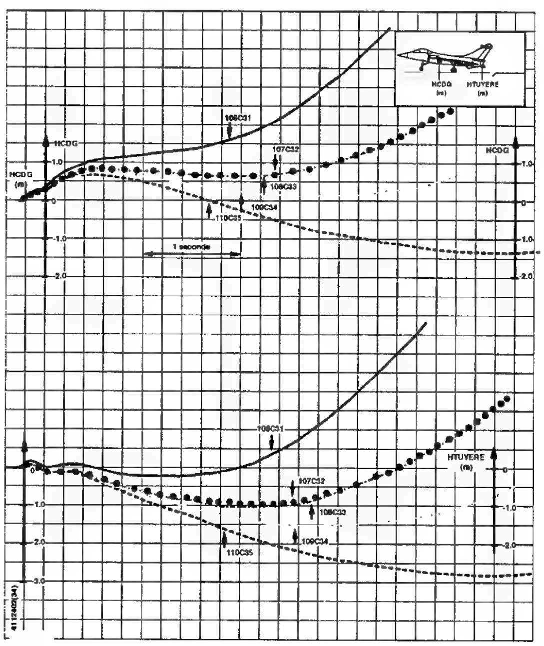
L'appontage fut essayé avec moins de surprises : le vérin de crosse nécessita plusieurs évolutions pour que nous optimisions son fonctionnement vis à vis des efforts transmis au fuselage et de la garde crosse/fuselage (l'amélioration de l'un pouvant impliquer une détérioration de l'autre). Ce travail était néanmoins prévu et la nécessité d'itérer ne nous étonna pas.

A partir de cette 2ème campagne d'essais sur base à terre, le déroulement de la mise au point se fit donc conformément à l'enchaînement prévu et de cette façon, somme toute, assez exemplaire.

Le 19 avril 1993, le RAFALE M01, piloté par Y. KERHERVE, appontait sur le Foch. Cette 1ère campagne en mer dura 2 semaines et demi pendant lesquelles 31 vols furent réalisés depuis le porte-avions.
On catapulta plein complet à plus de 5g ; des appontages dans diverses conditions de masse, pente et réglage de frein porte-avions furent réalisés ; les premières opérations de mise en oeuvre et de maintenance sur porte-avions permirent de vérifier la compatibilité d'un RAFALE et d'un porte-avions.

Depuis, les campagnes suivantes - 2 aux USA et 3 sur porte-avions - se sont déroulées sans rencontrer de sérieuse difficulté et à un rythme élevé. Les méthodes mises en oeuvre, y compris celles développées rapidement suite à la 1ère campagne se sont avérées efficaces. Deux exemples me semblent significatifs de la maîtrise que nous avons acquise dans le domaine des essais Marine :

- la recherche de la VMS (vitesse minimale sure de catapultage) est habituellement un exercice redouté qui impose une progression lente des essais en vol. Cette recherche fut menée durant la 3ème campagne sur porte-avions dans une configuration avec réservoirs et missiles (ce choix permet en cas de mauvaise surprise de larguer les réservoirs en sortie de catapulte et donc d'améliorer instantanément le bilan énergétique).
  En préalable, les 3 pilotes impliqués réalisèrent près de 150 catapultages sur le simulateur pour passer en revue tous les cas de pannes, de dégradation catapulte, de vitesse vent ... dans les conditions où nous prévoyions de faire les essais.
  Les essais sur avion quant à eux ne prirent qu'une journée : en 5 catapultages, on diminua la vitesse de catapultage de 10 kt ; la hauteur par rapport au pont du centre gravité avion 3 secondes après la sortie de catapulte passa de + 3 m à - 1.5 m ; l'objectif était atteint, le plus difficile - vu les conditions de vent du jour - avait assurément été de gouverner le bateau lors du dernier essai avec 1 kt d'aire (merci Commandant).



ENFONCEMENT EN SORTIE DE PONT

- Lors de la dernière campagne d'essais sur base à terre avec charges très lourdes, importantes dissymétries, centrages extrêmes, le rythme d'essai a battu des records : en 6 semaines nous avons réalisé 57 catapultages et 122 arrêts brin.

En synthèse, la 1ère campagne d'essais sur base à terre fut très différente de ce que nous avions prévu. En contrepartie, les problèmes rencontrés nous ont permis de renforcer notre capacité à modéliser des phénomènes dynamiques. Par la suite, on recolla à la logique de développement prévue avec des résultats satisfaisants et une efficacité meilleure qu'espérée, ce qui nous a permis d'économiser quelques mois d'essais.
Réussir des "premières" est toujours très gratifiant pour des ingénieurs : la démonstration de l'efficacité au catapultage de dispositifs tels que le dièdre et le train à restitution d'énergie sont à classer dans cette rubrique. Faire tomber des tabous n'est pas moins agréable : au début des essais de compatibilité à la mer, des spécialistes

nous affirmèrent qu'un avion à manche latéral était inapte au catapultage. La dizaine de pilote ayant été catapultés sur RAFALE peut heureusement infirmer aujourd'hui cet axiome. Loin d'ironiser, cela doit nous inciter à un certain recul vis à vis des idées toute faites.

Systèmes généraux

Par rapport au Mirage 2000, voire même au démonstrateur RAFALE A, les prototypes RAFALE possèdent de nombreuses nouveautés parmi lesquelles :

- des générations hydrauliques 350 bars,
- des générations électriques à fréquence variable,
- une génération d'oxygène autonome (OBOGS),

- un fonctionnement "tout numérique" avec une intégration des systèmes généraux au système global.

Afin de prendre en compte ces évolutions, les moyens de développement ont été adaptés :

- mise au point de l'OBOGS en vol sur avion de servitude avant d'équiper le RAFALE,

- intégration de tous les calculateurs des systèmes généraux sur banc global au même titre que le système d'armes,

- fabrication de stations mobiles couplables à l'avion pour observer et stimuler les systèmes généraux in situ.

En revanche, les impératifs économiques ont conduit à sacrifier sur l'autel des coûts certaines étapes du processus de mise au point avant intégration finale sur RAFALE. Ce choix fut délibéré et ne porta que sur des sujets qui apparaissaient sans risques sur la base de l'expérience Mirage 2000 et RAFALE A.

Aujourd'hui, la mise au point des systèmes généraux est terminée ; les logiciels "de série" des calculateurs sont en cours d'identification au banc d'intégration avant passage sur avion pour un contrôle final. Ces systèmes fonctionnent comme spécifiés et avec des performances conformes aux exigences des utilisateurs.

Il n'en reste pas moins que, pour certains systèmes, la mise au point sur avion s'est faite de façon optimale tandis que pour d'autres, la progression était laborieuse. Au tableau d'honneur des systèmes, je placerais volontiers l'OBOGS, la génération électrique et le système carburant dont la fiabilité ont été exemplaires tout au long des essais et qui n'ont nécessité que de minimes réglages. Ce n'est pas un hasard : le processus de spécification et de mise au point amont en ont été sans faille.

A contrario, nous avons eu des soucis sur avion avec les éléments sur lesquels nous avions procédé à des "impasses". Notre mauvaise surprise initiale sur la génération hydraulique en est caractéristique : les pompes hydrauliques 350 bars ont été développés chez l'équipementier et livrés directement sur le RAFALE C01 avant ses premiers points fixes. Aucun essai de pompe couplée à un circuit hydraulique représentatif de l'avion n'avait été réalisé.

Aussi, dès le 1er point fixe du C01, nous cassâmes une tuyauterie aval pompe en fatigue : la pompe, excellente à fort régime d'entraînement, générait en revanche un niveau de pulsation très élevé dès qu'elle fonctionnait à faible régime. Deux actions simultanées furent immédiatement entreprises :

- modifier la régulation de la pompe,

- développer un "banc d'intégration hydraulique haute pression" destiné à valider, y compris en endurance, la pompe modifiée et les tuyauteries aval.

Un mois plus tard, les essais sur avion pouvaient reprendre dans de bonnes conditions mais cet exemple doit être remémoré chaque fois qu'une étape d'un processus que l'on sait fiable est supprimée.
L'autre souvenir que l'on gardera de la mise au point des systèmes généraux de l'avion est le temps trop important que l'on met pour avoir un système bien fini. En effet, les essais au banc d'intégration puis sur avion mettent rapidement en évidence les évolutions que l'on désire. Mais dans le cas de systèmes totalement intégrés les uns aux autres, on s'interdit, à la fois pour des raisons d'analyse de sécurité et pour des motifs économiques, de les faire évoluer autrement que par étapes de développement. Il en résulte que des mois peuvent se passer entre le moment où une évolution simple est demandée et celui où le nouveau logiciel l'intègre. A ce rythme, certaines mises au point - le réglage d'une loi de Dirav par exemple - paraissent n'avancer qu'à trop faible allure. Une mise au point rapide me paraît exiger que, tout comme nous l'avons fait sur les commandes de vol, les logiciels de calculateurs des systèmes généraux incluent dès l'origine divers choix de logiques, divers choix de lois, divers choix de constante que le pilote peut activer pour optimiser le réglage.

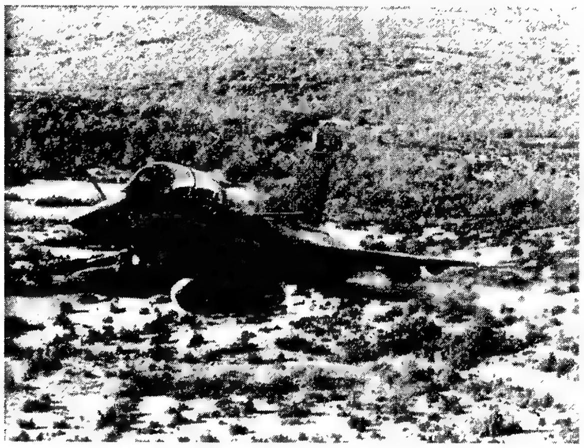
Cette capacité est en particulier essentielle pour tous les réglages sur lesquels le pilote a un avis et qui, suivant un processus itératif nécessitent un temps excessif de mise au point.

Emport - Séparations

Dans nos prévisions initiales, 2 éléments ont concouru à nous faire minimiser le temps consacré aux essais d'emport et de séparation :

- sur Mirage 2000, nous avons atteint un excellent niveau de corrélation entre la modélisation et le comportement de l'avion sur tous les chapitres concernés par les essais

d'emport : flutter, efforts structuraux, qualités de vol, couplages structure/commandes de vol. En conséquence, les vols d'ouverture de domaine avec charges se font avec une progression rapide en vitesse et en Mach. De plus, pour une configuration de charges, peu de sous-configurations nécessitent d'être testées en vol,



- concernant l'ouverture des domaines de séparation, de nouvelles méthodes ont été élaborées, basées plus que par le passé sur la modélisation des interactions aérodynamiques et nécessitant moins d'essais en vraie grandeur.

Aujourd'hui, les domaines de vol des configurations et sous-configurations du 1er standard sont ouvertes. Pour les charges les plus lourdes (Apache, réservoirs de 2000 l), les domaines ont aussi été ouverts. Nous avons ainsi pû, avant le lancement en série, conforter la définition de l'avion, notamment de sa structure et ses commandes de vol.
Ce travail a toutefois nécessité plus d'essais que prévu et des actions ont été lancées pour améliorer la modélisation des modes souples de l'avion. Pour l'avenir, nous restons sur nos prévisions initiales de volume d'essais d'emport.

Les essais de séparation des charges du 1er standard sont soit terminés (Magic, réservoir pendulaire de fuselage) soit en cours (Mica, réservoirs pendulaires de voilure). Jusqu'ici les essais se sont déroulés selon la progression prévue et dans les temps impartis.

Système de navigation et d'armements

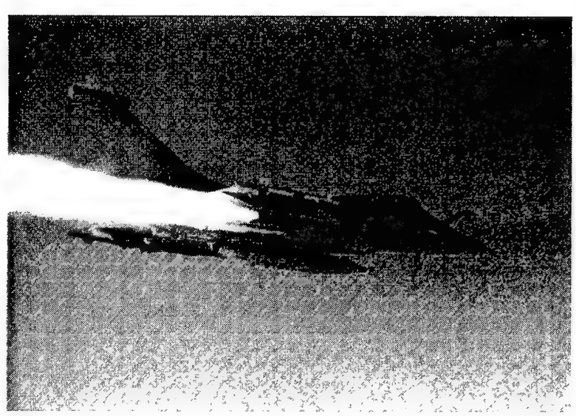
Plus les systèmes sont complexes et ambitieux et moindre doit être le poids relatif des essais en vol d'intégration et de mise au point des fonctions dans le processus de développement. L'amélioration constante de la phase de spécification, l'utilisation de simulations pilotées de très grande représentativité et la mise au point amont des équipements majeurs ont pour but de :

- limiter les vols sur prototypes,

- minimiser les risques de voir ces vols remettre en question les choix faits plus amont.

La "relégation" des équipes d'essais à ce rôle de contrôleur des travaux bien faits ou à un rôle encore plus ingrat de porteur de la mauvaise nouvelle ("le résultat est mauvais, veuillez reprendre votre copie") serait rapidement démotivante si un transfert ne s'était pas opéré : les pilotes et ingénieurs d'essais prennent une part active à la spécification initiale et à sa validation sur simulateur. L'expertise des équipes d'essais est donc mise à profit, en ingenierie concourante, tôt dans le programme avant que les remises en question n'aient des conséquences budgétaires notables.
Le processus de développement du RAFALE s'est établi sur ces règles dès le départ. En conséquence, le volume des vols prévu pour la mise au point système est resté modeste comparé à l'ambition du système développé.

Actuellement, vole un système comprenant toutes les fonctions du 1er standard. Dans quelques mois, ce système sera mis entre les mains de pilotes opérationnels pour une évaluation dont l'objectif est de figer un état de référence pour les avions produits dans le 1er standard. Dès aujourd'hui un nombre important d'éléments parait acquis :



RAFALE

Le rôle actif de l'Etat dans les essais en vol

Marc TOURTOULON
Responsable de l'équipe intégrée des essais en vol RAFALE
Centre d'Essais en Vol

L'ambition technique et financière affichée par le programme de l'avion RAFALE, vue au travers des yeux des managers chargés de mettre en place les organisations capables de mener à terme ce projet, ne laissait guère d'espoir aux différentes chapelles qui pouvaient exister çà et là : dialogue et partage devraient être les deux maîtres mots du programme.

L'époque où l'industriel réalisait le produit que le client avait spécifié et que ce dernier évaluait après plusieurs années de développement était définitivement révolue. Les conséquences sur un programme de problèmes découverts seulement en fin de développement (i. e. lors de l'évaluation finale) sont telles qu'elles condamnaient à elles seules les méthodes précédentes. Tous les moyens permettant de raccourcir les délais entre la spécification et l'évaluation étaient recherchés et systématiquement mis en avant. Il fallait améliorer le dialogue entre les utilisateurs et les concepteurs afin d'adapter le plus rapidement possible le produit au besoin, tout en garantissant une parfaite maîtrise à long terme des objectifs techniques, calendaires et financiers du programme. Les difficultés majeures devaient être identifiées et traitées le plus en amont possible tout en évitant surtout de piétiner sur des détails de moindre importance.

Un autre axe d'économies substantielles consistait à éviter la duplication des essais et des moyens mis à disposition du programme. Certains essais sont en effet effectués une première fois par l'industriel dans le cadre normal du développement, une seconde fois par le client pour vérifier les clauses d'acceptation contractuelles, et éventuellement une troisième fois par les utilisateurs lors des évaluations opérationnelles. Indépendamment de la responsabilité des essais qui reste dans ses grandes lignes conforme à la répartition classique entre l'industrie et l'état, un partage de l'exécution des essais devait être recherché.

EQUIPE INTEGREE

Découlant d'une réelle volonté d'application des principes précédents aux essais en vol du RAFALE, l'équipe intégrée Etat/Industrie a été mise en place dès le début du programme. Un des principaux objectifs chiffrés de cette organisation était de réduire environ de moitié par rapport aux programmes précédents les essais étatiques de vérification de conformité. Ainsi, seulement 5% de l'emploi du temps des prototypes Rafale devaient être consacrés aux tâches étatiques. En tenant compte des hypothèses retenues concernant les cadences de vol (7 à 10 vols par mois en développement et 1 vol par jour en évaluation), on obtenait un total de 15% des vols consacrés aux constats techniques et évaluations opérationnelles.

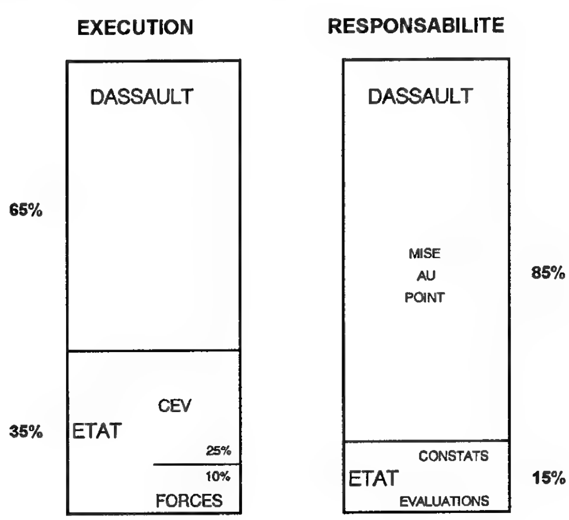


Fig. 1 : Répartition prévisionnelle des vols

Afin d'éviter la répétition des points d'essais en évaluation, une participation étatique aux essais en vol de développement placés sous la responsabilité de Dassault Aviation était convenue. Des équipes d'essais du Centre d'Essais en Vol

(CEV), mais également des pilotes d'essais et spécialistes de l'Armée de l'Air (CEAM) et de la Marine Nationale (CEPA) constituait l'Equipe Intégrée Partie Etat (EIPE) qui avait à charge d'exécuter 15% des vols d'essais des prototypes Rafale ; cette part s'élevait même à 30% pour l'exécution des vols de mise au point du système d'armes.

Evitant une duplication coûteuse des vols, cette participation importante de l'Etat aux essais industriels permettait également d'obtenir très tôt dans les développement des avis consolidés des utilisateurs opérationnels sur les différents sous-systèmes, laissant ainsi plus de temps pour la réalisation d'éventuelles adaptations. Les souhaits initiaux d'amélioration du dialogue étaient ainsi également promus par ce travail en équipe intégrée.

Dans le même but d'améliorer l'efficacité, les équipes de Dassault Aviation se voyaient offrir une participation aux essais en vol réalisés par le CEV. Ceux-ci permettaient au responsable du développement du système d'appréhender le fonctionnement réel des équipements, et ce bien plus tôt et surtout bien mieux que ce qu'il pouvait le faire auparavant où il ne connaissait le comportement des équipement qu'au travers de modèles informatiques prévisionnels sommaires.

RETOUR D'EXPERIENCE

Après cinq années de fonctionnement de l'équipe intégrée des essais en vol Rafale, les résultats obtenus sont plutôt flatteurs. Les participations réciproques Etat/Industrie aux essais ont été parfaitement respectées sans induire aucune ingérence qui aurait été préjudiciable à la bonne entente nécessaire.

La bonne application au cours du développement du partage des vols a été rapidement considérée comme un indicateur du bon fonctionnement de l'équipe intégrée. Le constat que l'on peut dresser à ce point du programme est tout à fait révélateur du bien fondé des répartitions initialement choisies.

Les équipes étatiques ont réalisé plus de 400 vols d'essais sur les prototypes Rafale et seulement une centaine de vols d'évaluation. Si on tient compte des évaluations au sol de la mise en oeuvre et de la maintenance, c'est environ 3.5% de la durée calendaire d'utilisation des prototypes Rafale qui auront été consacrés aux épreuves de vérification. L'objectif initial de 5% est largement atteint.

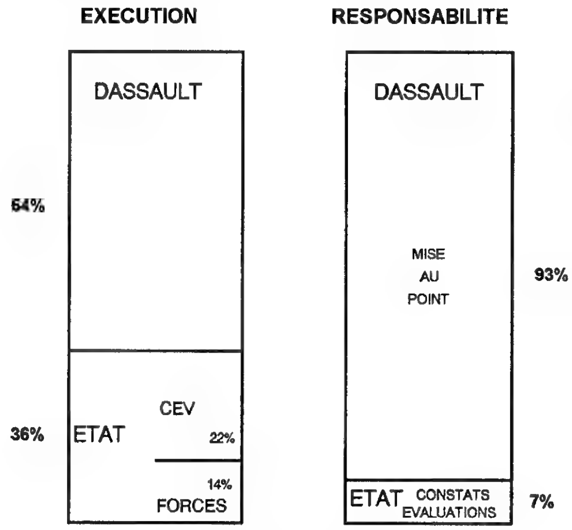


Fig. 2 : Répartition effective des vols

Dans le domaine restreint des vols dits de "spécificités marine" (catapultages, appontages et prises de brins) une répartition particulière des vols fut convenue. Etant jugé non raisonnable d'écarter à priori une des trois entités concernées par ces essais, le partage retenu a été de 45% pour Dassault Aviation, 35% pour le CEV et 20% pour le CEPA. Cette répartition des vols de spécificités marine assurait aux pilotes de maintenir l'entraînement leur permettant d'exécuter les essais avec toutes les garanties de sécurité souhaitées. On en arrivait ainsi au paradoxe suivant où les deux pilotes de l'Etat (CEV et CEPA) exécutaient plus de la moitié des vols sur des campagnes pourtant sous la responsabilité de Dassault Aviation ! Quelle meilleure preuve peut-on trouver de la bonne intelligence dans laquelle ces principes de partage ont été appliqués ?

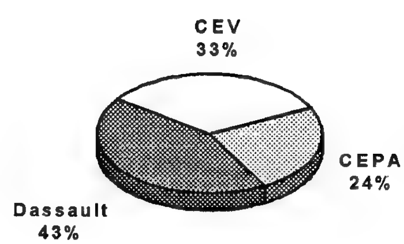


Fig. 3 : Partage des vols "spécificités marine"

THE EH101 DEVELOPMENT PROGRAMME

Mark Hazzard
Flight Test Department
GKN Westland Helicopters
Lysander Road
YEOVIL BA20 2YB, UK

SUMMARY

This paper describes the EH101 helicopter flight development programme from initial conception to the present day. Lessons learnt during the testing phase are highlighted and significant milestones achieved are detailed. In particular the early development testing is described in some detail.

1 THE REQUIREMENT

In the early 1980's it was becoming apparent to the Royal Navy (RN) that a replacement needed to be sought for the Sea King helicopter, the new aircraft to enter service in the early years of the 1990's. Similarly the Italian Navy (Marina Militaria Italiano or MMI) had reached a similar conclusion independently. Each service had approached their native helicopter manufacturing companies (Westland Helicopters (WHL) as was and Agusta Helicopter respectively) to initiate feasibility studies of the replacement aircraft. With a similar specification drawn by both services it became obvious that a collaborative venture to fulfill both requirements was a good idea, hence an independent company called E H Industries (EHI) was set up to manage the programme. This company, based in London, would be a joint WHL and Agusta holding. EHI realised that the payload, range, reliability and overall aircraft performance required by the two Navies would provide a potential world beating civilian aircraft to replace the many Sikorsky S61 type aircraft operating offshore, similarly the internal dimensions required could be used to produce a long range medium size tactical transport and Utility aircraft.

The bold decision was made to develop 3 core variants of the same airframe to meet Civil and Military rules and to fulfill Naval, Civil passenger and civil/military utility and Search and Rescue roles simultaneously, the EH101 project was born in 1981 with the signing of Memorandum of understanding (MOU) 2, Project Definition.

It was realised that with such an ambitious programme a large amount of testing, both on the ground and in flight would be required. It was therefore decided to construct 9 pre production flight vehicles, PP1 - PP9 inclusive and several non flight complete airframes or powered rigs. The most significant of which are the Avionics airframe for lightning/EMC testing and the 'GTV' (Ground Test Vehicle or 'Iron Bird'). The GTV is a ground based transmission, electrical system and rotor rig powered by the requisite engines. It is fully representative of the transmission system and its use to support the flight development programme will be described later.

The initial workshare and allocation of the 9 aircraft is described below.

A/C	Type	Location	Task
PP1	Basic Naval	WHL	Basic Vehicle Development
PP2	Basic Naval	Agusta	Basic Vehicle Development
PP3	Basic Civil	WHL	Basic Civil Development and AFCS
PP4	RN	WHL	Basic Naval Systems/EIS Development

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

PP5	RN	WHL	RN Mission Systems Development
PP6	MMI	Agusta	MMI Mission Systems Development
PP7	Military Utility	Agusta	Basic Utility Vehicle Development
PP8	Civil PAX	WHL	Civil Specific Development
PP9	Civil Utility	Agusta	Civil Specific Development

In addition the GTV was based at Agusta.

The initial allocation of development tasks has remained fairly constant, primarily due to the inherent build standards defined at initial build and to the complexity of the instrumentation required, the most significant alteration to the allocation of tasks was that PP4 undertook installation tests of the RN selected RTM322 engine, more of which later.

At this point a few salient features of the aircraft as <u>initially</u> flown are pertinent.

AUW (kg)	13000
Nr (%)	100
Vne (kias)	120
Transmission	4640 SHP

The aircraft has a fully articulated rotor head fitted with advanced planform blades derived from the British Experimental Research Programme (BERP) that gained WHL the absolute helicopter speed record in 1986.

2 THE EARLY DAYS

The flight programme was initiated on 9 October 1987 when WHL Chief Test Pilot Trevor Egginton applied collective and PP1 became airborne at Yeovil, England watched by most of the factory staff, the programme soon gathered momentum when PP2 joined the flying programme in November 1987.

After 50 hours cumulative flying the aircraft was presented to the Test Centres of the UK and Italy for the first Official Test Centre (OTC) review involving UK and Italian military personnel. Vibration levels of both 1R and 5R were higher than expected, some handling problems, especially during low speed manoeuvring were apparent, aircraft performance figures were disappointing, and at high speed a lateral shake, christened 'shuffle' was noted. As development testing progressed, the inefficiency of operating the two instrumented basic development aircraft (PP1 and PP2) at different sites in two countries was noted. It was decided that the most beneficial way to improve the situation would be to base the aircraft at the same location; Cascina Costa in Italy, the home base of Agusta Helicopters was the logical choice. The weather being better for testing and with Agusta facilities on site to provide support to the transmission and rotor systems which were regarded as the critical components at this phase of the programme. PP1 left the UK in October 1988 and joined PP2 to inaugurate the 'Single Site Operation' (SSO).

3 SINGLE SITE

The Single Site Operation was a major undertaking for both companies but justified the effort put into the operation, as the aircraft successfully completed basic vehicle development. With hindsight the operation should have been planned from the beginning, A few details of the techniques used and results obtained are described below.

3.1 Prioritisation

Prior to the start of the operation the issues requiring development were prioritised in order to allocate technical expertise to providing a solution.

3.2 Specialisation

Due to the workshare between Agusta and Westland agreed at the contract signature it was obvious that either one

windspeed environment and many of the above fixes were easy to quantify in the calm air in Italy, the testing would have been impossible in the UK, again justifying the effort put into the SSO.

As with all testing there are tradeoffs and compromises to be made, however the aerodynamic issues discussed above seemed to interact well and a benefit in one area would manifest itself in another so the entire aerodynamic improvement task was effectively one package that was retrofittable to the entire EH101 fleet, this is summarised in Figures 7 and 8. At the end of SSO solutions existed to:

a) Shuffle
b) Level flight power consumption
c) Hover power consumption
d) Tail rotor authority
e) Exhaust gas reingestion and installed power losses.

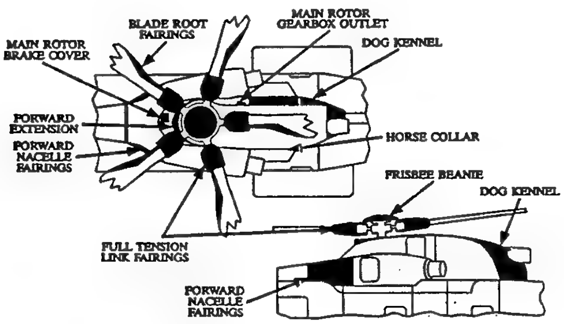


FIG 7) AERODYNAMIC IMPROVEMENTS 1

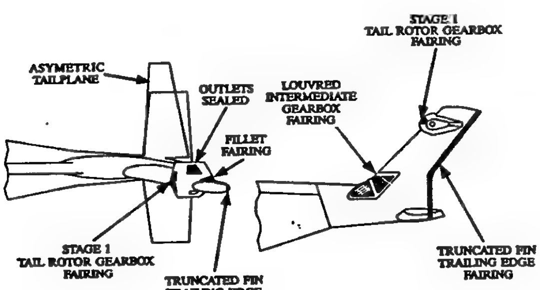


FIG 8) AERODYNAMIC IMPROVEMENTS 2

4.3 5R Vibration Improvements

Levels of airframe vibration were higher than expected at blade passing frequency (5R). Structural modifications were incorporated to stiffen the fuselage as well as passive vibration absorber devices which are traditionally used to cure vibration problems in rotary wing aircraft . Both a double stacked Lynx helicopter main rotor head mounted vibration absorber and a trial installation of cabin mounted vibration absorbers were assessed and showed noticeable reductions in some 5R levels within the cabin but with a large weight penalty. Meanwhile back in Yeovil a new system of active vibration absorbtion using compliant gearbox mountings hydraulically actuated had been developed. Known as ACSR (Active Control of Structural Response) this revolutionary system uses the inherent dynamic response of a fuselage to counteract blade induced vibrations. The EH101 installation is the first practical active vibration absorbtion system in use and was developed on PP3 in the UK. This system at a stroke massively reduced the 5R vibration levels (in some cases by 90%) and is fitted as standard to all EH101 Aircraft. See Figure 9.

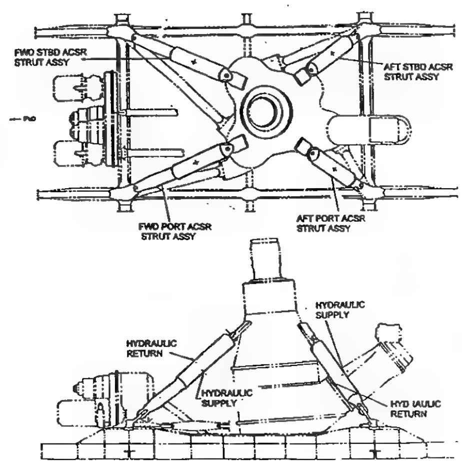


FIG 9) ACSR INSTALLATION

4.4 SSO Achievements

In summary after the Single Site Operation completed its remit there existed or were in design improvements in all areas under development. In the final months a further OTC assessment was carried out to verify the SSO findings, The conclusions matched the companies. Many of the solutions were not flight tested as the GTV and ground rigs were used to quantify the improvements to transmissions and structural components but being under the control of the SO itself helped to integrate this aspect of the development task into the whole aim of the operation, to cure the problems.

By comparison the improvement in aircraft characteristics before and after single site are as follows;

	Before SSO	Post SSO
AUW (kg)	13000 kg	14290 kg
Nr (%)	100	100/102
Vne (kias)	120	167
Transmission	4640 SHP	5200 SHP
Altitude	10000 Ft	15000 Ft
Low Spd Env	20 kts	50 kts

The aircraft was now able to be used throughout its envelope to increase its mission performance and to serve as a basis for specific systems development.

5 SIGNIFICANT TRIALS POST SSO

Post Single Site all 9 aircraft were flying with new priorities, predominately with respect to PP1 - PP4. Basic vehicle envelope expansion continued with the aim of achieving a limited civil variant release in 1994, an icing clearance and with the awarding of the Royal Navy Merlin contract, integrating of the RTM322 engine into the EH101 airframe (more of which later). The tragic loss of PP2 in January 1992 had a major impact on the programme and milestones slipped approximately a year.

PP5 had a successful first flight with all mission systems and 'glass cockpit' working including a night landing. This boded well for an intensive mission system and naval specific test programme which included Ship Interface trials with the Royal Navy Type 23 frigates HMS Norfolk, HMS Iron Duke and HMS Northumberland (Fig 10). This series of tests proved the maintainability of the aircraft in the naval environment and its operability of frigate sized vessels, including cross winds of 40 kts and ship deck motions in all axes. The hydraulic deck lock and deck handling system was tested and gave confidence that longer duration tests will not be a problem.

FIG 10) PP5 ON HMS IRON DUKE

PP3 carried out trials in Denmark and Canada and returned with an icing release down to -10°C; it proved flight in snow (both precipitating and recirculating) was feasible and that cold soaking overnight still allowed starting and flight. The heated blades were exercised which provided valuable data to be read across to the production heated blade and the forthcoming cold trial in Sweden, again on PP3. The instrumentation fit on PP3 was extensive and included fixed and rotated cameras, ice and snow detector system and comprehensive strain gauging and temperature monitoring including transparencies and main and tail rotor hubs and blades (FIG 11)

FIG 11) PP3 IN SNOW

PP7 and PP1 carried out the major load data gathering task required to substantiate the 10000 hr structural fatigue life required by the customers and proved the CT7-6 engine was exceptionally reliable.

The major drive during 1993 and 1994 was achievement of the Civil Airworthiness Authority Type Certification (TC) of the EH101, in both Passenger and Utility Variants. by CAA, RAI and FAA simultaneously. Most of the development fleet

TORNADO INTEGRATED AVIONICS RESEARCH AIRCRAFT (TIARA)

A.D.Brown
A J Stocks
Defence Evaluation and Research Agency
Probert Building
Farnborough, Hampshire GU14 0LX, England

SUMMARY

The paper describes the rôle, major features and flight trials programme of the Tornado Integrated Avionics Research Aircraft - TIARA. This significantly modified F2A(T) Tornado , ZD902, is the flagship of the trials fleet currently operated by the Defence Evaluation and Research Agency (DERA), an Executive Agency of the UK Ministry of Defence.

TIARA is a multi-sensor, multi-rôle trials facility intended to demonstrate a "total systems integration" concept. It not only directly supports military customer programmes but also has sufficient capacity for collaborative programmes with other research organisations.

Following a major conversion programme, ZD902 is now currently being used for the evaluation of IR sensors and helmet mounted displays. The future installation of the Blue Vixen AI radar will complete TIARA as a research facility and allow trials on sensor data fusion to begin.

1 INTRODUCTION

The Defence Evaluation and Research Agency (DERA) is an Executive Agency of the UK Ministry of Defence. Various parts of the organisation have links with aviation going back many years. In fact it was at the Farnborough site that Colonel Sam Cody made the first manned flight in the UK in 1908. This tradition has been maintained and today the operation of trials aircraft in support of military and civil customer programmes is an important activity. DERA currently owns a fleet of 14 aircraft covering helicopters, laboratory and fast-jet types (Table 1).

These aircraft are operated by DERA's Air Fleet Department (AFD) from an airfield at Boscombe Down, Wiltshire and are flown by military pilots including test pilots. All the aircraft have been modified to varying degrees for the incorporation of experimental equipment. Relevant design, manufacture and installation activities are generally carried out using AFD's own personnel and facilities, although tasks may be sub-contracted if appropriate.

AIRCRAFT	Tail No.
Laboratory:	
Andover C Mk1	XS 646
Andover CC Mk2	XS 790
BAC 1-11 (200)	XX 105
BAC 1-11 (400)	XX 919
BAC 1-11 (500)	ZH 763
HS 748 Series 1	XW 750
Fast-jet:	
Harrier DB T2/4	XW 175
Hunter T7	WV 383
Tornado GR1	ZA 326
Tornado F2A(T)	**ZD 902**
Rotary-wing:	
Lynx AH7	ZD 285
Lynx AH7	ZD 559
Sea King HC4	ZB 506
Wessex HC2	XR 503

Table 1 DERA Trials Fleet

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

This paper is concerned with one particular aircraft, namely Tornado ZD902, which is now the flagship of the DERA trials fleet.

ZD902, a Tornado F2A(T) trainer version of the Air Defence Variant (ADV), (Fig.1) has undergone a major conversion to an advanced flight trials facility designated TIARA - Tornado Integrated Avionics Research Aircraft.

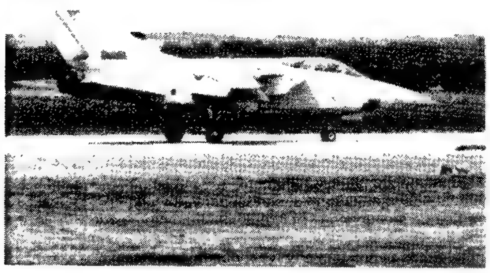


Figure 1 F2A(T) Tornado ZD902

This paper describes the rôle and capability of the aircraft and then outlines some current and future flight trials programmes.

2 ROLE OF TIARA

The primary rôle of TIARA is to support the military customers' programmes with particular, but by no means exclusive, emphasis on the air defence aspects. The location and recognition of targets through the development of all-weather sensor systems, and the reduction of aircrew workload are of particular interest. Consequently, the intention is that TIARA should demonstrate the operational benefits of "total systems integration" encompassing all aspects from the sensors through to the man-machine interface (MMI).

Because of the apparent emphasis placed on single pilot military fighters, the front cockpit has been significantly modified to provide a single seat fighter environment.

The rear crew member acts as a safety pilot and carries out such tasks as controlling and monitoring the experimental systems and data recording.

A major objective of the "integration" programme is to evaluate and demonstrate the principle of multi-sensor data fusion.

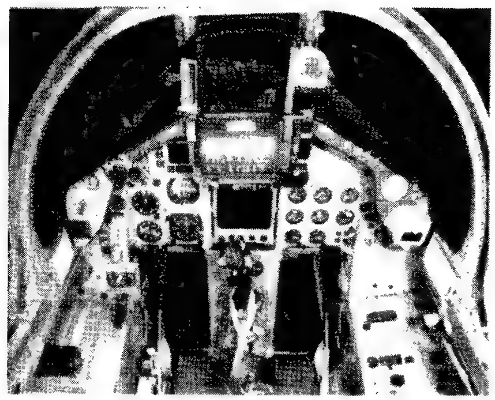


Figure 2 Original front cockpit of ZD902

3 TIARA FEATURES

3.1 Front cockpit

The original front cockpit of ZD902 with its vast array of electro-mechanical instruments, shown in Fig. 2, was completely removed and replaced by a more advanced diffractive head-up display (HUD), CRT full-colour head-down displays (HDDs) and a "hands on throttle and stick" (HOTAS) capability (Fig. 3).

An experimental wide field of view, diffractive HUD is being used, providing the pilot with a 30° x 20° field of view. It has a raster/cursive capability and potential enhancements to this device include improvements to the pilot's up-front control panel (UCP) and increased output luminance. If required for trials reasons, however, a HUD with a more conventional field of view may be fitted as an alternative.

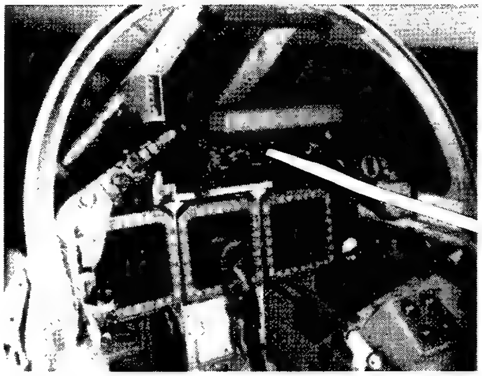


Figure 3 TIARA's "glass" cockpit

Three 6 ins. square, full colour, raster/cursive shadowmask CRTs with integrated control panels are mounted in-line across the cockpit and provide the primary head-down displays (HDDs). This technology was chosen because of the immature state of flat-panel displays existing in 1992 when such decisions were made.

The 20 buttons around each display are soft keys allowing rapid multi-moding of the displayed information. In addition to standard flight information the displays can also present specialised experimental formats.

For flight safety reasons a set of electro-mechanical (EM) standby flight instruments have been retained together with the main engine temperature and RPM parameters.To provide space for these instruments, the existing central warning panel (CWP) has been moved to a position just below the middle HDD, although this has required the physical separation of the display and electronics sections.

The standard displays for both the radar homing & warning receiver (RHWR) and missile management system (MMS) have been removed from the front cockpit due to the limited panel space available, although equivalent information will be presented on the HDDs. The RHWR and MMS displays have, however, still been retained in the rear cockpit, the latter being necessary to preserve the emergency stores jettison capability.

The cockpit also has provision for a range of helmet mounted devices including simple sights and integrated helmets incorporating CRTs and image intensifiers. Both AC and DC electro-magnetic head position sensor systems (HPSS) can be fitted for use with the helmet mounted displays (HMDs). This aspect is discussed further in section 5.4.

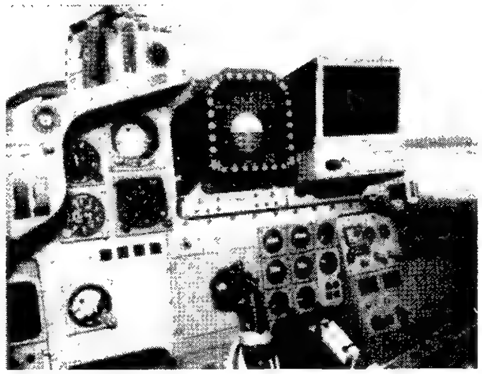


Figure 4 TIARA's rear cockpit

In due course, attention will be given to upgrading other aspects of the cockpit e.g replacement of the standard UHF/VHF radio frequency selection box by a flat panel display to allow for possible voice or "touch screen" operation.

For general cockpit monitoring purposes, up to 5 miniature CCD colour video cameras can be installed. Currently, one camera views forward over the aircraft nose and others may view the HDDs or the pilot's actions as dictated by the trials requirement.

3.2 Rear cockpit

The rear cockpit has deliberately been left relatively unchanged in the short-term,

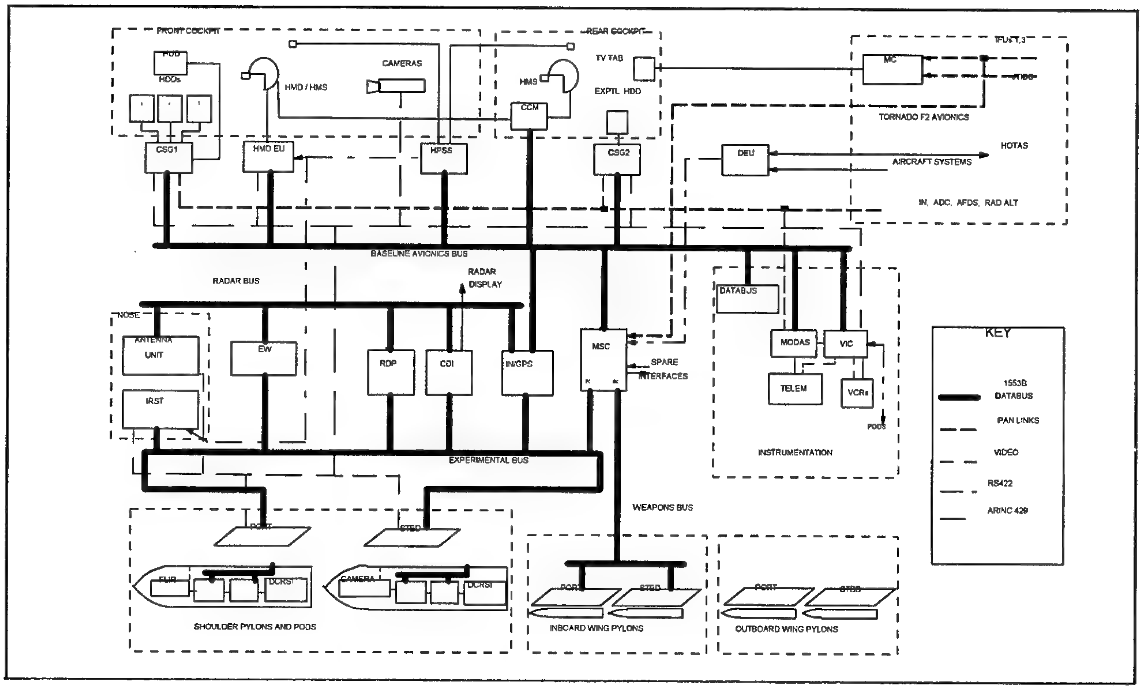


Figure 5 TIARA avionics architecture

especially as far as the electro-mechanical instruments are concerned, thus preserving the overall Tornado systems integrity. However, one of the TV TAB displays has been removed thus making it possible to install an alternative display. Currently, a shadowmask display of the same type as used in the front cockpit is fitted, although it could readily have been some alternative technology such as a flat panel liquid crystal display (LCD). Should side-by-side display comparisons be required e.g shadowmask CRT and LCD, then such provision can also readily be made.

Control panels are installed in the rear cockpit side consoles for the recording system, video cameras, telemetry and experimental power distribution. These include a data loading system which by means of a small data card can be used to initialise the experimental systems for the mission in question rather than having a number of different control panels, one per equipment.

Needless to say, an important requirement is for both cockpits to be fully night-vision goggle compatible and this process is nearly complete.

3.3 Avionic systems architecture

To provide the necessary experimental flexibility a new avionics architecture has been installed based on a multiple 1553B databus system. These have been designated as the baseline avionics, radar, experimental sensors and weapons buses. However, the use of the existing Panavia point-to-point data links has been retained and for specific applications RS422 and ARINC 429 communications introduced.

The current configuration is shown schematically in Fig. 5. It comprises a number of distinct functional areas :-

(a) standard Tornado avionics

(b) front cockpit

(c) rear cockpit

(d) experimental interfaces, bus controllers and electronic units

(e) instrumentation

(f) airborne sensors including IRST, EW and the AI radar with its associated units e.g radar data processor (RDP) & controls and displays interface (CDI)

(g) pylon mounted equipment (shoulder, inner & outer pylons)

At the present time no main computer (MC) outputs are used by the experimental system. Instead, information is taken directly from the standard Tornado avionics e.g inertial navigation system, air data computer and radio altimeter, via the serial Panavia datalinks. Approved Pan Link tee-modules provide the necessary degree of isolation and signal buffering in order to preserve the integrity of the basic aircraft avionic systems. Thereafter, the signals can either be used directly or else accessed via the 1553B baseline avionics bus. The conversion is made within one of the computer symbol generators (CSG) to ensure minimum latency.

A dedicated laser gyro based inertial navigation (IN) system provides accurate time tagged attitude and navigation data for the experimental system. It also feeds the radar bus thus ensuring accurate stabilisation information is available at a high (240 Hz) data rate. It also incorporates a global positioning system (GPS) capability which fulfils a number of functions both experimental and operational.

The so-called mission computer (MSC) performs a multi-function rôle including bus controller for the baseline avionics bus, experimental sensors bus and the weapons bus. It can also provide non-standard analogue, synchro and discrete interfaces and receive digital information from HOTAS and other aircraft systems via the data encoder unit (DEU).

Since there are many requirements for high speed processing on the aircraft e.g to emulate the in-flight trajectory of a missile such as AMRAAM, the MSC will encompass such functions. To achieve this degree of flexibility the MSC comprises a ruggedised VME system with multiple 68040 processors and is primarily programmed in Ada.

Display symbol generation (cursive, raster and cursive in raster flyback) is provided by means of two computer symbol generators (CSGs) capable of receiving data from 1553B and Pan Links as well as analogue and discrete signal sources. One CSG drives all four electronic displays in the front cockpit; the second provides a reversionary source for the HUD, serves experimental displays such as the HDD in the rear cockpit and also provides an output for video recording purposes. These units are modular in design, currently based on the 68020 processor and with expansion capability built in.

Provision has been made in TIARA for the incorporation of EFABUS (Mil.Std. 3910) which provides fibre-optic transmission and has a theoretical 20 Mbit/sec capability. However, until the appropriate interfaces are readily available for the avionic equipment and sensors, the commissioning of this system will be postponed.

A cockpit computer module (CCM) has been incorporated as a means of reducing the number of separate equipment control panels needed in the aircraft. It allows a general purpose panel to be reconfigured using software, provides a data read-out capability and also allows rapid data entry via a "data card".

3.4 Air Interception radar

Instead of the AI 24 Foxhunter radar normally fitted in F3 Tornados, a GEC-Marconi Avionics Blue Vixen multi-mode AI radar will be installed of the type currently fitted to UK Sea Harriers. This option was selected because the radar incorporates more modern technology and, because it has been specifically designed for single crew operation, provides a more appropriate man-

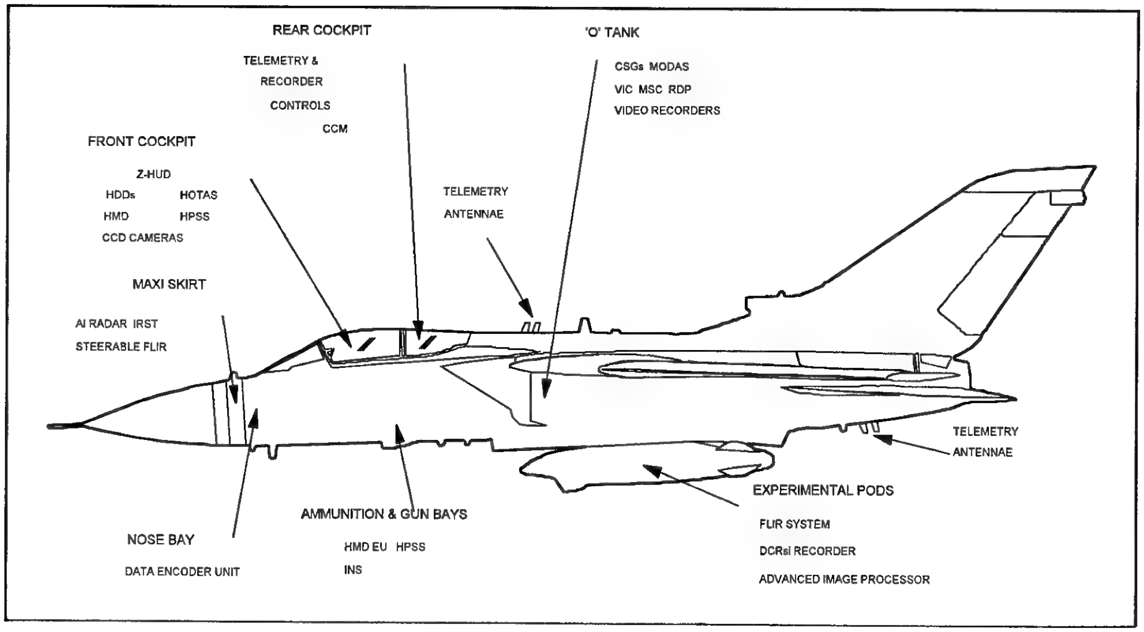


Figure 6 TIARA equipment locations

machine interface for the front crew-member. Another significant benefit arises from its relatively small physical size which will enable an infra-red search & track (IRST) sensor to be co-located in the nose, providing the initial basis of the sensor data fusion programme.

Although there will probably be a reduction in performance of some parameters such as maximum detection range, the research is primarily concerned with concepts and hence this is not considered to be a major problem.

The intention is to integrate the radar into the system as part of the experimental avionics and in Fig. 5 the radar data processor (RDP) is shown connected to the experimental sensors bus as well as its own radar bus. (A dedicated fibre-optic link connects the RDP to the antenna assembly.) The optimum manner to integrate the radar is still being studied. However, design work on the physical installation is well advanced using representative space models and the actual radar will be delivered in 1997.

3.5 Recording system

As shown in Fig. 5, the basic recording system comprises 5 video cassette recorders (VCRs), a general purpose modular data acquisition system - (MODAS) and two dedicated Heim databus recorders.

An onboard telemetry system allows a limited range of parameters and a video channel to be transmitted to a ground station. This will provide trials personnel with on-line information concerning the progress of the trial, supported by TV pictures from one of the cockpit cameras.

In addition, for certain trials, it is proposed to use a high bandwidth digital recorder which will be flown in one of two environmentally conditioned pods capable of being fitted to shoulder pylons beneath the aircraft.

3.6 Equipment locations

Fig. 6 shows the approximate locations of the various equipment on the aircraft. The three major areas are the nose bay, the

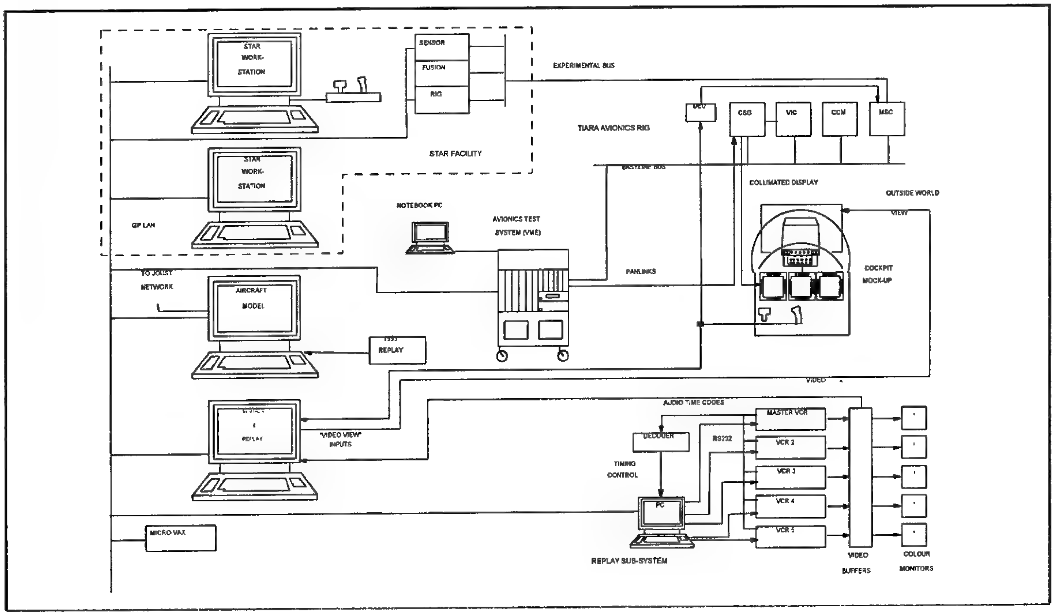


Figure 7 TIARA avionics ground rig

ammunition bay and 'O' Tank, the latter having been converted from a fuel tank to an avionics bay. Despite the removal of 'O' Tank, sorties well in excess of one hour are possible and this extends to two hours with wing tanks. However, the flight refuelling probe has also been retained as another means of enabling longer duration sorties to be flown if required.

The capability will also exist to carry experimental equipment in the pods referred to above e.g FLIR sensors, recorders or additional computers. Conventional stores can be carried on the in-board wing pylons e.g fuel tanks, AIM9L Sidewinders and ASRAAMs. The reinstatement of the out-board wing pylons, as fitted to Tornado GR1s, is being considered since it would provide a valuable additional trials capability.

4 TIARA AVIONICS GROUND RIG

To support the aircraft, a comprehensive avionics ground rig has been built, housed in mobile trailer. It is now currently based at Boscombe Down along with the aircraft although it could be brought back to Farnborough if necessary. The rig is used for a range of tasks including systems integration, software development, and the functional testing of experimental units.

In addition, the rig may be connected to a self-standing representative TIARA cockpit and a collimated outside world display providing the forward (48°x 36°) scene for the pilot if required. This allows some of the experimental display formats to be fully stimulated and assessed by the aircrew and, in due course, will provide a mission rehearsal/debrief capability.

The major hardware elements are shown in Fig. 7. Two Silicon Graphics (SG) computers provide the processing power for the Tornado aerodynamic model and the outside world display. A VME based system converts the ethernet LAN data into equivalent 1553B and Pan Link form for use by the aircraft experimental equipment under test. An

important feature of the rig is that it can be linked via ethernet with the adjacent Sensor fusion & Tracking Applications Rig (STAR). This will allow sensor fusion algorithms to be subjected to man-in-the-loop assessment using the representative TIARA cockpit prior to actual flight trials.

The rig can also be networked with the JOUST™ beyond visual range (BVR) combat simulator. This facility allows multi-player operational assessments of weapon/avionics/platform combinations in realistic air combat scenarios. The TIARA cockpit will be used as a JOUST station both to assess the man-machine interface (MMI) aspects and validate simulator results prior to flight trials.

5 TIARA TRIALS PROGRAMME

TIARA is a pan-DERA facility and supports a wide range of military applied research programmes, technology demonstrators and projects. The flight trials programme underway covers the following general research areas :-

(i) Infra-red sensors

(ii) Helmet mounted displays (HMD)

(iii) Sensor data fusion (SDF)

(iv) Off-boresight weapon aiming

(v) Man-machine interface (MMI)

(vi) Systems integration

Brief descriptions of these trials programmes are given in the following sections.

5.1 IR sensors

The evaluation of IR sensors represents a major trials activity on TIARA and is concerned with long range passive detection and identification of targets, for both air-to-air and air-to-ground operations. An infra-red search and track (IRST) system is installed in the nose of the aircraft, collocated with the radar (Fig 6). Both sensors are physically mounted in the Tornado maxi-skirt for ease of access and installation.

By interchanging some of the IRST modules it is possible to convert the system to a head steered FLIR (HSF). This can be used in conjunction with an integrated aircrew helmet as discussed later.

In addition to the above, TIARA can fly with dual podded FLIR sensors and it is intended to carry out advanced processing on the IR sensor data to enhance the image detection, recognition and tracking capability.

The above IR programmes are supported by a strong sensor modelling activity.

5.2 Helmet mounted displays

The HMD will undoubtedly have a major impact on future cockpits since it adds significantly to the flexibility of the MMI. To gain early experience of such a system a technology demonstrator programme has produced a binocular HMD, Viper 2, designed for fast-jet usage and incorporating CRTs. The numerous flight safety issues associated with head mounted equipment have been addressed and the device has been installed in TIARA ready for flight trials. Its evaluation will provide a valuable insight into all the human factor and integration issues involved. Of particular interest will be the use of the HMD to slave the AI radar, IRST or steerable FLIR, or alternatively, the radar to reverse cue the pilot. In addition, research will be required into the specific HMD symbology to be used and the relative rôles of the HMD and the HUD.

Because of the complexity of the problem it is likely to take a number of iterations before a totally acceptable HMD solution is achieved. Many of the underlying technologies are, however, being actively pursued by DERA in collaboration with Industry.

5.3 Sensor data fusion

This programme will be aimed at establishing the operational effectiveness of multi-sensor

data fusion for long range target detection, identification and interception, by day and by night, in all weather conditions. The intention is to provide the capability to assess a range of fusion techniques and algorithms. Both track and measurement level fusion will be evaluated and scenarios flown will draw extensively on experience gained from the JOUST simulator trials. Research is continuing on the algorithm development using STAR to provide the initial means of assessment with TIARA providing the means of validation.

The AI radar and the IRST will be the first sensors considered for the fusion process. Both exhibit different temporal and spatial characteristics and accuracies but their collocation should remove one of the major sources of difficulty involved in the harmonisation process.

An essential element of the programme will concern the development of display formats that can effectively present tactical information to the pilot in order to maintain his level of situation awareness under high workload conditions.

Incorporated within STAR is a dedicated SDF rig which comprises a multiple processor configuration using Motorola 68020s and 68040s. SDF software is in Ada and the system architecture includes a fibre-optic EFABUS. The modular construction of this rig allows it to be configured in a manner representative of a number of possible airborne configurations. The intention is therefore to link the SDF rig with the TIARA rig cockpit via ethernet thus effectively emulating the aircraft architecture prior to the start of flight trials.

5.4 Off-boresight weapon aiming

Helmet Mounted Sights (HMS) are far simpler devices than HMDs and yet can still provide significant operational benefits. TIARA will capitalise on the considerable experience gained within DERA from previous HMS flight trials. Both the radar and the IRST will be capable of slewing via the HMS.

The head position sensing system (HPSS) is a critical element when using any helmet mounted device as part of an aircraft system e.g for off-boresight weapon aiming, and considerable effort has been given to identifying the most effective technique.

Based on recent trials experience, particular emphasis has been given to achieving the maximum possible size of head motion box for the pilot. Although a number of potential techniques exist, making them work in a fast-jet cockpit environment can be very difficult. To date, the main experience has been with the AC electro-magnetic system but a DC system will be used with the Viper 2 helmet. The TIARA cockpits are capable of being equipped with either system.

The initial flight trials are attempting to study the operational issues and any problems experienced by the pilot when attempting large off-boresight weapon aiming. Captive missile seeker heads will be used for the evaluation and a digital Mil Std 1760 interface will be available.

5.5 Man-machine interface

Containing pilot workload is an important element of the research programme and essential to maintain the operational effectiveness of the single seat fighter. Appropriate expertise already exists within DERA on the measurement of workload and these techniques will be used on TIARA to study aircrew behaviour in a range of scenarios. The miniature video cameras will be used to record pilot activity from which a time-line mission analysis can be implemented. Cognitive processes will be deduced by careful debriefing of the pilot during mission replays on the ground.

The level of workrate is influenced strongly by the man-machine interface (MMI). As already mentioned earlier, TIARA has a "glass" front cockpit with HOTAS and a number of discrete control panels. Work on cockpit moding and display formats has been underway using the TIARA rig to establish a

baseline system. The use of a speech recognition interface is a feasible option and allowance has been made for the installation of such equipment.

The MMI research covers a range of aspects including basic data measurement and advanced display technology. Of particular relevance is the use of flat panel displays e.g LCDs and the intention is to evaluate such technology as it becomes available.

5.6 Systems integration

The aircraft is already fitted with a standard radar homing and warning receiver (RHWR) system and has provision for the installation of a Joint Tactical Information Distribution System (JTIDS). The intention is to integrate these with the radar and other onboard sensors as part of a collaborative programme with Industry to confirm the expected operational benefits. The resulting combination should significantly assist in the rapid generation of an accurate tactical air picture for the pilot, including prioritised threats.

6 CONCLUSIONS

This paper has briefly described the proposed rôle, major features and flight trials programme of DERA's Tornado ZD902, designated TIARA (Tornado Integrated Avionics Research Aircraft). The aircraft is a multi-sensor, multi-rôle trials facility intended to demonstrate a "total systems integration" concept. It will directly support a number of Applied Research Programmes, Technology Demonstrators and Projects.

Following a major conversion programme, ZD902 is now undertaking experimental trials flying. The procurement and integration of the experimental equipment necessary to attain the TIARA concept is virtually complete, apart from the AI radar which will be delivered in 1997.

Among TIARA's prime features are a modern avionics architecture, a multi-sensor capability and the creation of a modern single-seat fighter environment in the front cockpit.

The first major flight trials are concerned with infra-red sensors and helmet mounted displays. Following installation of the Blue Vixen radar, the prime objective will be to evaluate and demonstrate the application of multi-sensor data fusion in a multiple threat environment.

TIARA (Fig. 8) will provide a unique fast-jet trials facility for the Defence Evaluation and Research Agency during the next decade. It will also have sufficient capacity to support a number of collaborative programmes with Industry.

Figure 8 TIARA on trials

Investigations on Handling Qualities and Aerodynamic Characteristics of EUROFIGHTER 2000 at DAIMLER-BENZ AEROSPACE Flight Test Centre

Dr.-Ing. Hans-Christoph Oelker, Erfried W. Muthsam
Daimler-Benz Aerospace AG, Military Aircraft Division
Postfach 1149, D-85073 Manching

Abstract

Currently the development flight test evaluation of EUROFIGHTER 2000 is under way. The present paper emphasises on analysis methods for flight mechanical and aerodynamical evaluation suitable for a very agile, highly unstable fighter aircraft at DAIMLER-BENZ AEROSPACE flight test centre. Methods are summarised and illustrated with some representative results.

Analysis methods in the time domain such as simulation of flown manoevres and in the frequency domain such as Z-transformation and Fourier analysis methods for system stability evaluations are presented. DASA's aerodynamic parameter identification method is presented. It resembles a unique equation decoupling approach to cope with the problems arising from the analysis of unstable aircraft. Representative results are given, which demonstrate the analysis capabilities of the presented methods.

1 Introduction

Next century's fighter aircraft for the air forces of Spain, Italy, United Kingdom, and Germany will be the EUROFIGHTER 2000 (EF2000). It is developed jointly as a very agile fighter aircraft by industrial partners of these four nations (CASA for Spain, Alenia for Italy, British Aerospace, BAe, for the United Kingdom and Daimler-Benz Aerospace, DASA, for Germany); the basic geometry is given in Fig. 1. The characteristic feature of this configuration is the canard, resulting in an aerodynamically highly unstable aircraft. It is therefore controlled by a full authority quadruplex redundant flight control system (FCS).

The current status of the programme is already a good way ahead in the development flight test evaluation of the aircraft. Flight test tasks have been split up between the four partner companies. At the moment four of seven development aircraft (DA's) are flying. DA1, the first flying aircraft, is allocated at DASA Manching, while DA2 is allocated at BAe Warton. These two development aircraft share the tasks for expanding the flight envelope as follows: DA2 expands the envelope basically in the direction of increasing velocity, whereas DA1 basically expands the envelope towards increasing angles of attack (AOA) respectively normal load factors n_z. Fig. 2 gives, as an example, an overview of wind up turns so far performed on DA1 with a reduced control law standard in the FCS. Since DA1 is also considered to be the 'data gathering aircraft' for validation of the aerodynamic stability and control dataset, flight conditions have been tested several times, as can be seen from the figure, with different load factors for purposes of aerodynamic parameter identification (APID). In this context the present paper emphasises on evaluation techniques which are suited to gain sufficient information on the validity of the mathematical model in use.

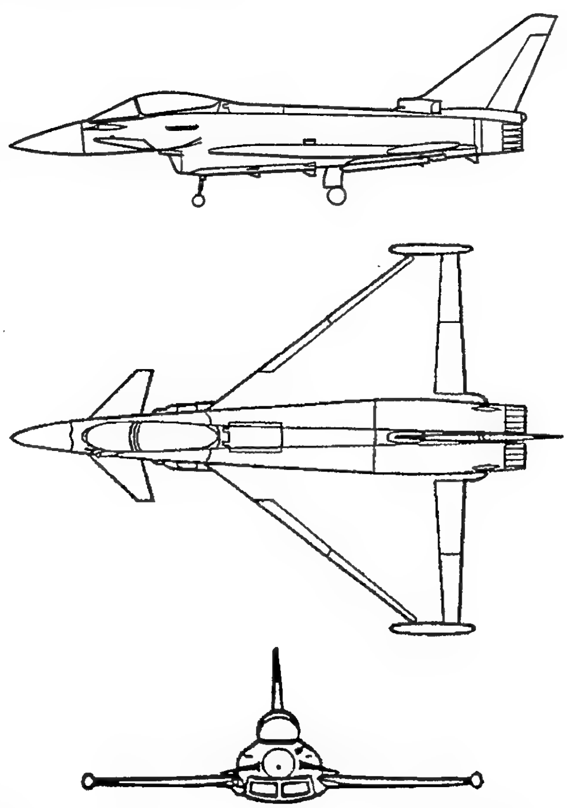


Fig. 1 Geometry of EUROFIGHTER 2000 Configuration

The current analysis approach at DASA is a mixture of online monitoring and analysis whilst the aircraft is up in the air and detailed offline analysis after the flight. During the flight emphasis is put on the total system, which in this context will be called the augmented aircraft. Due to the desired rapid progress during one flight the main emphasis is on monitoring the aircraft state with time histories (scroll plots) and cross plots. Due to limited personell detailed online

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

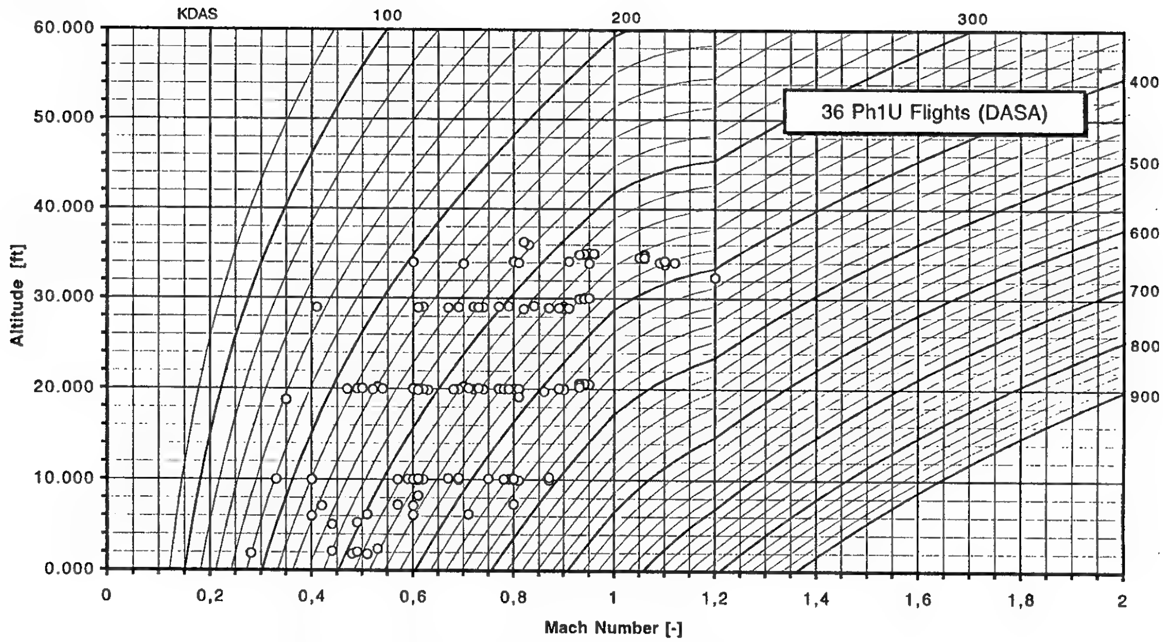


Fig. 2 Overview of performed Wind Up Turns

analysis procedures are not applied yet, the installation is still planned for this year though. One advantage of offline analysis procedures is the availability of on-board recorded data with generally a very high fidelity instead of not seldom disturbed telemetry data during online analysis. Also offline analysis gives much more time to think about the results, thus aircraft safety relevant decisions can be prepared in a better manner. Offline analysis also offers the possibility of investigation of the unaugmented aircraft via APID methods. In the following an overview of analysis techniques applied is given, which will be followed by some example results demonstrating the integrated use of these tools.

2 Analysis Methods

2.1 Flight Dynamics Simulation Check (FDSC)

Flight dynamics simulation check describes the process of repredicting the time histories of a flown manoeuvre after this manoeuvre has been finished. This can be done online in the quicklook room or offline in the office. For analysis on EF2000 this process is made up as follows:

The model is based on a nonlinear simulation kernel with 6 degrees of freedom with respect to the aircraft motion. This kernel has access to the nonlinear aerodynamic dataset. Linearisation of the aerodynamic data is not performed, for each integration step nonlinear aerodynamic data is used. In addition this kernel has access to the full model of the control laws as incorporated into the aircraft. Modelling of relevant hardware characteristics is included as well, e.g. actuation dynamics. This model is used at all EF2000 partner companies for development purposes. At DASA flight test certain additions to the model code have been made in order to evaluate flown manoeuvres at measured flight conditions with measured pilot's inputs.

Integration of flight data into a simulation programme is a simple straight forward procedure as long as unaugmented aircraft are under consideration. For augmented aircraft additional aspects have to be considered, especially for a controller with an integration of feedback signals as it is the case for EF2000. A principal sketch of the control law structure for the longitudinal motion of the aircraft is given in Fig. 3. The mentioned integrator is clearly visible. In reality this structure is much more complex. Controller gains are generally scheduled accordingly to the aircraft's state, thus this information must be fed into the controller in addition to the measured output of the integrator, which resembles the 'history' up to the start of the manoeuvre of interest. Two ways of control law initialisation are possible:

- Before start of the simulation analysis a trim calculation is peformed. In this case the trim target is either measured AOA at the beginning of the manoeuvre or measured n_z. Then the model is trimmed on the basis of the existing dataset. Therefore trimming for AOA cannot provide measured n_z and vice versa, since it must be expected that the dataset is slightly different from the real aircraft's aerodynamics, also control surface positions may not be in the exact position as in flight. The trimming procedure also provides a value for the integrator output, based on the dataset. For the mentioned reasons its value can differ slightly from the flight measured value. After the trimming is finished the simulation can be started using measured pilot's inputs from flight.

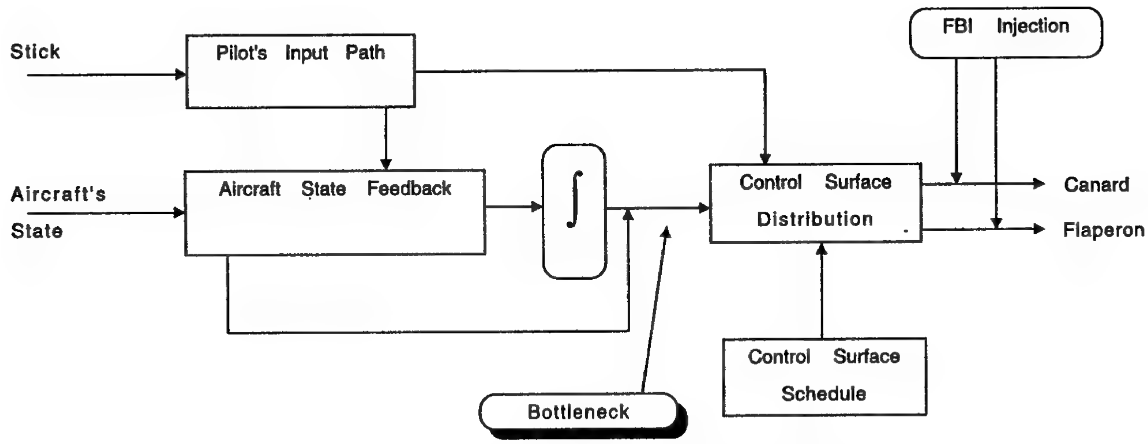


Fig. 3 Principal Control Law Structure (Longitudinal Motion)

- As much as possible data is taken from the aircraft at the beginning of the manoeuvre under consideration. A prerequisite is that all necessary data (control law specific air data, integrator output) is available via flight test instrumentation (FTI) recording. Now the necessary data to initialise the controller is taken from flight data as well as the trim condition. The simulation model is started with these values and flight measured pilot's inputs.

The advantage of the first procedures is that standard flight data are incorporated into a known process. Disadvantages are the dependancy on the aerodynamic model for the initial conditions and the necessary computing effort to calculate the trimming position. The second approach needs more FTI parameters but does not need the additional computing time for a trim calculation. It is therefore also better suited for online application of FDSC. For the results given here the second approach has been choosen.

Results of FDSC are well suited to gain a quick qualitative overview of model fidelity. If questions arise, model variations can be applied easily (e.g. variation of certain aerodynamic derivatives with respect to tolerance investigations) and their influence can be evaluated in comparison with flight data. FDSC results can also be used as inputs to other analysis tools, so with these tools so called predictions can be produced.

2.2 Low Order Equivalent System (LOES) Analysis

The low order equivalent system analysis approach is used to gain insight into dynamics of systems of complex order. For this analysis the assumption is made, that the observed system is approximately linear within the investigated amplitude range. In the time domain an appropriate system excitation is necessary with respect to the frequency spectrum of interest. The transformation into the frequency domain is then achieved via Z-transformation. Calculation of system poles and Eigenvalues is performed successively.

The advantage of the Z-transformation is the fact that the solution of a simple difference equation in the time domain provides the coefficients of the transfer function in the Z-domain. The basic equation , as described in Ref.1, is as follows:

$$y_i = -\sum_{k=1}^{N} \frac{a_k}{a_0} y_{i-k} + \sum_{k=0}^{M} \frac{b_k}{a_0} x_{i-k} \tag{1}$$

with
- y_i = system response at time i
- x_i = system excitation at time i
- a_k = coefficients of the denominator polynomial of the transfer function
- b_k = coefficients of the numerator polynomial of the transfer function
- N = degree of the denominator polynomial of the transfer function
- M = degree of the numerator polynomial of the transfer function

The solution of this equation provides the transfer function H(z) in the Z-plane:

$$H(z) = z^{(N-M)} \frac{\sum_{k=0}^{M} \frac{b_k}{a_0} z^{(M-k)}}{\sum_{k=0}^{N} \frac{a_k}{a_0} z^{(N-k)}} \tag{2}$$

From this equation the poles of the denominator can be calculated, representing the Eigenvalues of the system. Then the relationship:

$$z = \exp\{sT\} \tag{3}$$

yields the transformation from the Z-plane into the more convenient S-plane whereas T is the sampling intervall. Using this formula Eigenfrequency ω_N and damping ζ of a pole can be derived as follows:

$$|z| = \sqrt{z_{real}^2 + z_{imag}^2}$$
$$\theta = \arctan(z_{imag} / z_{real})$$
$$\omega_N = \sqrt{\left(\frac{1}{T}\ln|z|\right)^2 + \left(\frac{1}{T}\theta\right)^2} \tag{4}$$
$$\zeta = \left(-\frac{1}{T}\ln|z|\right) / \omega_N$$

From Eq. 2 the impuls response in the time domain can be derived via partial fractions. From there the system response of the LOES can be calculated via the folding integral and compared with the originally measured system response, thus giving a qualitative measure of the fidelity of the LOES approximation.

LOES analysis has been performed very successfully at DASA flight test for 'conventional' unaugmented aircraft during envelope expansion flying, e.g. RANGER 2000 or unaugmented TORNADO. Analysis has been performed online, the results gave immediate information about the aircraft's stability. Post flight comparisons with APID results showed very good agreement. For augmented aircraft this method provides a tool describing the handling qualities as 'felt' by the pilot only. Information about the aircraft's stability margin cannot be derived. This requires a special analysis of the controller, as described below.

2.3 Frequency Domain Analysis

Frequency domain analysis is performed with the conventional discrete Fourier transformation. Applications are analyses of control law stability margins and of aircraft pilot coupling criteria.

2.3.1 Control Law Stability Evaluation

For stability margin evaluations the transfer function of the system with open feedback loop is calculated. With a known model it can be calculated in a relatively easy manner. For simple single branch systems the open loop transfer function can be derived from e.g. the measured closed loop transfer function with the well known formula:

$$F_{open} = \frac{F_{closed}}{1 + F_{closed}} \tag{5}$$

For EF2000 this formula is valid only at that point, where all feedback signals are fed through one common signal path. This is called the bottleneck and is indicated in Fig.3. For theoretical calculations the open loop transfer function can easily be calculated there. In flight test this can only be done if a proper signal injection is available.The current control law configuration does provide test signal injection into the controller, but not at the bottleneck.

For stability margin calculations some provisions are given in the controller. Fig. 3 shows at the output of the controller to the control surfaces two signal injections generated by the frequency and bias input facility (FBI). This tool is an integral part of the controller and can be used to generate arbitrary signals, which could be injected anywhere in the controller. Current software status allows injection of these signals at those points where the control surface excitation signal leaves the controller, namely at the canard and flaperon demand signals for the longitudinal motion; frequency sweeps are available. Injection of a signal at one of these points mathematically opens the feedback loop there, thus enabling analysis for a partially open loop transfer function only. Partially open, because the feedback loop over the other control surface is still closed. Ref. 2 provides a formula which calculates the open loop transfer function at the bottleneck from the partially open loop transfer functions at the canard and flaperon injection points. It is as follows:

$$F_{openBottleneck} = \frac{\left(F_{closedCanard} + F_{closedFlaperon}\right)}{1 + \left(F_{closedCanard} + F_{closedFlaperon}\right)} \tag{6}$$

Thus the application of two frequency sweeps via the FBI at the canard and at the flaperon demand signal path enables the analysist to calculate the open loop transfer function at the bottleneck for a given flight condition. In practice the aircraft has to fly to the desired test conditions twice and two FBI manoeuvres have to be flown. For future testing FBI signal excitation at the bottleneck will be available, thus reducing required testing time to 50%.

2.3.2 Aircraft Pilot Coupling Evaluation

The second application of Fourier transformation analysis is the evaluation of aircraft pilot coupling criteria. This procedure represents a straight forward analysis with a transfer function resulting from the stick input as system excitation and the aircraft's attitude as system response. For this analysis only pilot produced frequency sweeps are currently available. It is also planned to use the FBI for future testing on this subject.

2.4 Aerodynamic Parameter Identification (APID)

The verification of the used aerodynamic model is performed using aerodynamic parameter identification (APID) techniques. At DASA flight test an extended version of the well known output error approach has been used highly successful for many years.

The output error approach is based on a comparison of flight measured data of the aircraft's state with corresponding data derived from a simulation. The difference between these results, the output error, is evaluated by a maximum likelihood algorithm in order to find the desired corrections to the aerodynamic derivatives. Due to the mathematical nature of the estimation algorithm the involved simulation step has to

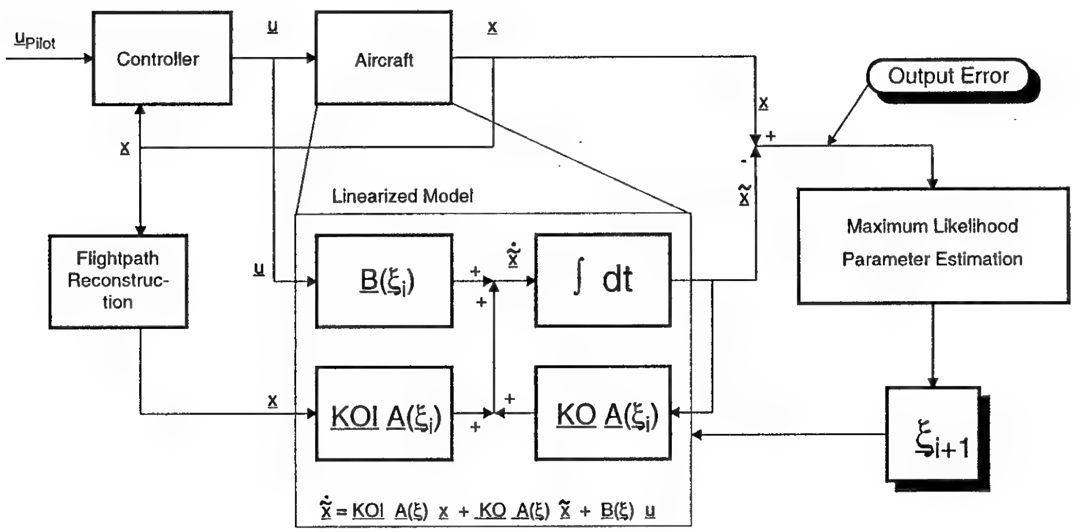


Fig. 4 Schematic Overview of Aerodynamic Parameter Identification with Equation Decoupling Technique

be based on a linearised aerodynamic model. For stable aircraft this procedure is well known and well established. For unstable aircraft this procedure fails because integration of the flight mechanical equations will generally diverge to infinite values, see e.g. Refs. 3 and 4. Therefore an output error comparison cannot be performed anymore. Ref. 3 gives a procedure, which introduces artificial stabilisation during integration of the equations. The method requires additional computational effort. At DASA flight test another approach has been followed, the equation decoupling technique as introduced by H. Schäufele in Ref. 5.

The basic idea of the equation decoupling techniques is based on the introduction of flight measured aircraft state variables into the integration of the flight mechanical equations. The usual state equation

$$\dot{\tilde{\underline{x}}} = \underline{A}(\underline{\xi})\,\tilde{\underline{x}} + \underline{B}(\underline{\xi})\underline{u} \qquad (7)$$

with $\tilde{\underline{x}}$ = simulated state vector
$\underline{u}$ = control vector
$\underline{\xi}$ = parameter vector
$\underline{A}$ = system matrix
$\underline{B}$ = control matrix

is then changed to

$$\dot{\tilde{\underline{x}}} = \underline{KOI}\underline{A}(\underline{\xi})\,\underline{x} + \underline{KO}\underline{A}(\underline{\xi})\,\tilde{\underline{x}} + \underline{B}(\underline{\xi})\underline{u} \qquad (8)$$

with $\underline{KOI}$,$\underline{KO}$ = decoupling matrices
$\underline{x}$ = measured state vector.

The decoupling matrices, introduced in Ref.5, are complementary, which means that at equal positions one matrix contains a '1' whereas the other contains a '0' at this position. The entire process, output error approach and equation decoupling, is summarised in Fig. 4. For general use at DASA also a flight path reconstruction is part of the process. The final result is a set of flight validated aerodynamic parameters, which now can be used to calculate the flight mechanical properties of the aircraft.

The given APID procedure has been successfully used at DASA flight test for different aircraft of stable and unstable basic airframe characteristics.The main programme of the past years was TORNADO, also experience on unstable aircraft has been gained, e.g. the German F-104 CCV (Control Configured Vehicle) in the early eighties and EAP (Experimental Aircraft Programme) in the late eighties. Also helicopters have been investigated successfully.

Currently the procedure is integrated in an extensive programme package. The analysis procedure is heavily automated although still giving enough possibilities for model variations in the APID process. Fig. 5 gives an overview. At DASA flight test strong efforts are undertaken to incorporated this process into an online environment. This would automatise the engineering work to collect manoeuvres and considerably reduce processing time.

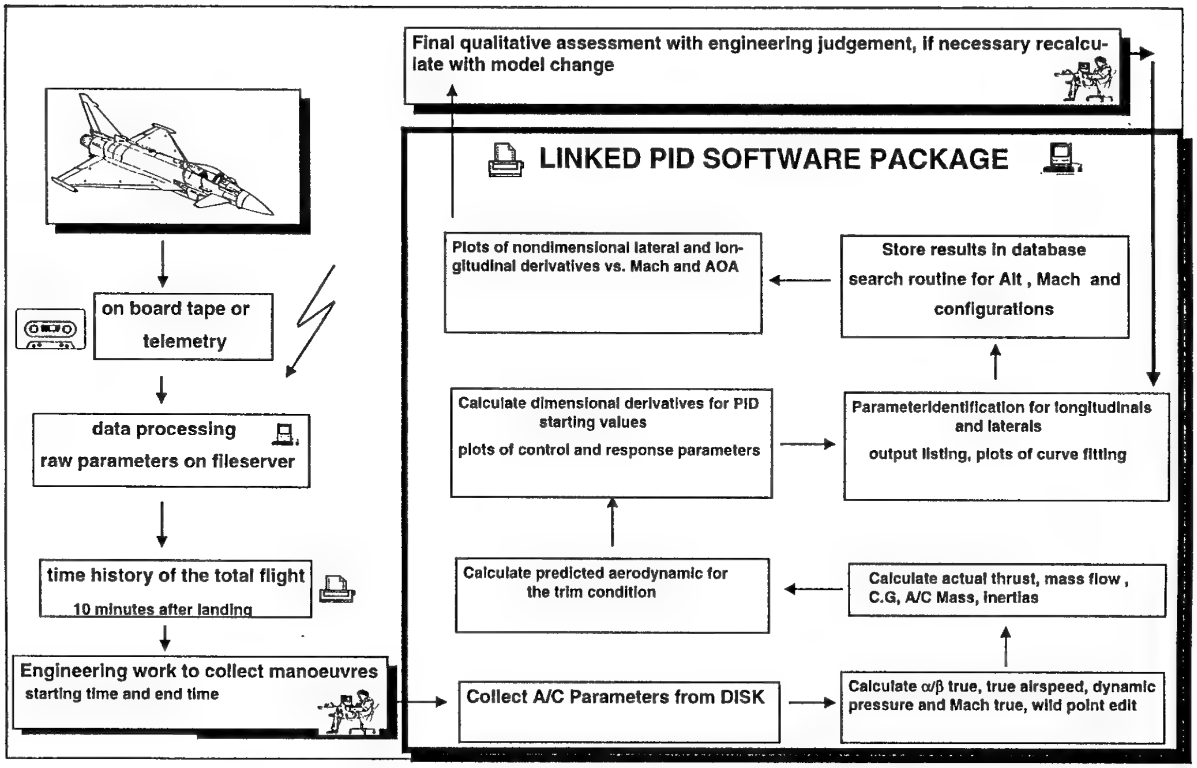


Fig. 5 Overview of Aerodynamic Parameter Identification Process

3 Representative Results

In the following some representative results for each of the described procedures above will be given. All results are from recent testing on EF2000. Since it is a military project analysis results are generally classified. Therefore certain information, which may be of interest to the reader, has been omitted.

3.1 Flight Dynamics Simulation Check (FDSC)

A typical result of FDSC analysis is given in Fig. 6. Part a) of it gives the measured traces for the pilot's inputs. The manoeuvre under consideration is a wind up turn to the left. Part b) shows the comparison of flight measured and simulated variables of the longitudinal motion. Generally very good agreement could be achieved, except for the Mach number, where some deviations can be observed. This may be due to an unsufficiently accurate modelling of the engine, at the time the Mach number curves start to deviate the pilot made an input via the throttle. Part c) shows the comparisons for the control surface positions. Finally part d) gives the leading edge position as well as two control law parameters, the integrator output and a calculated AOA value, which is used for scheduling purposes. The increasing deviation between measured and simulated traces towards the end of the manoeuvre is due to the cumulation of small starting errors during the integration process of the flight mechanical equations. Nevertheless the still very good agreement for all curves gives an indication of the high fidelity of the available model.

a)

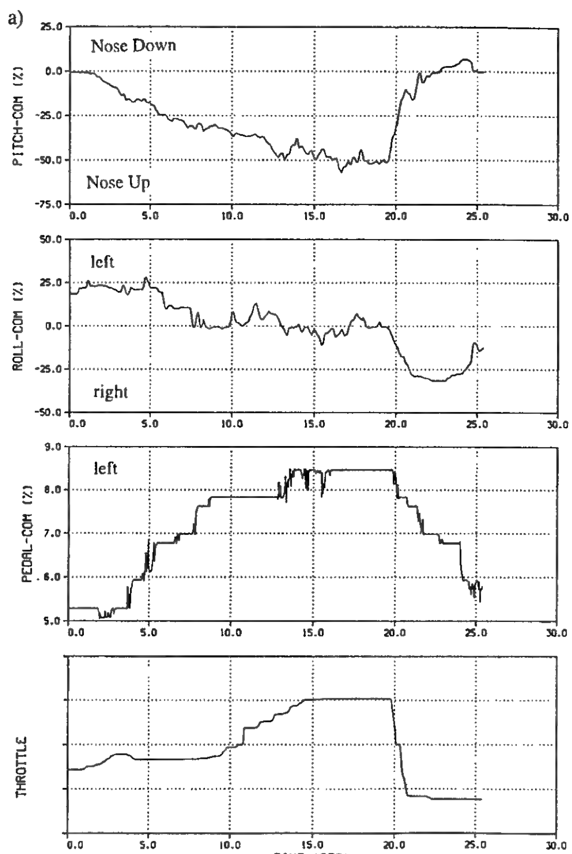
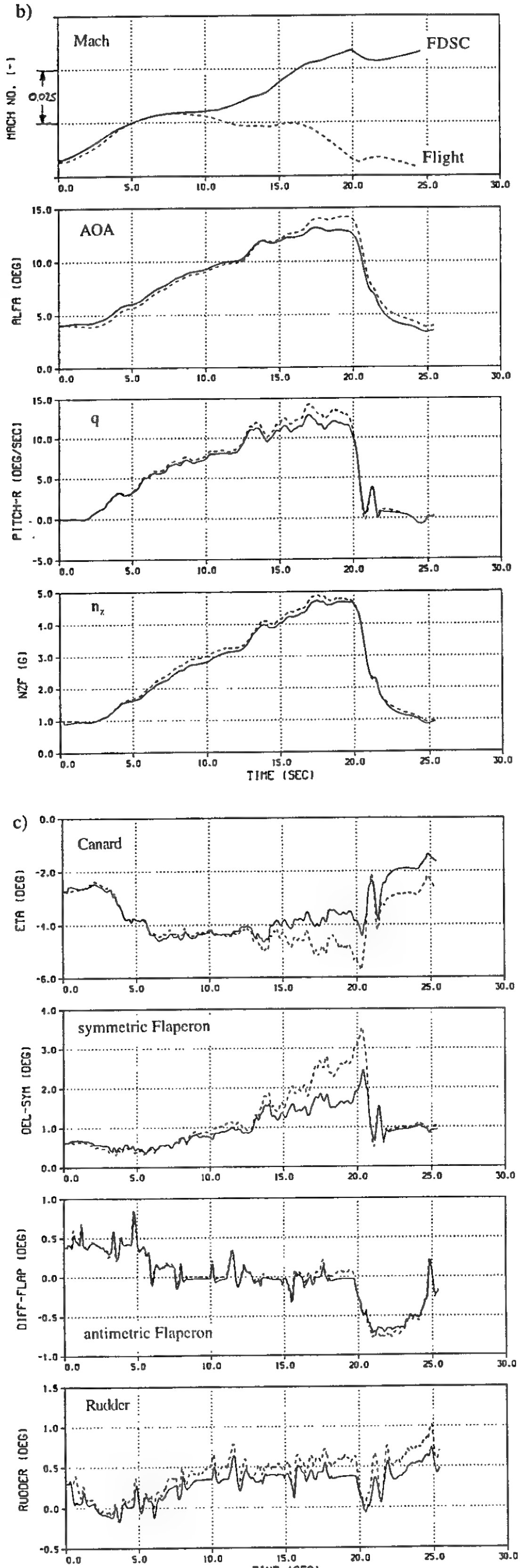


Fig. 6 Results of Flight Dynamics Simulation Check



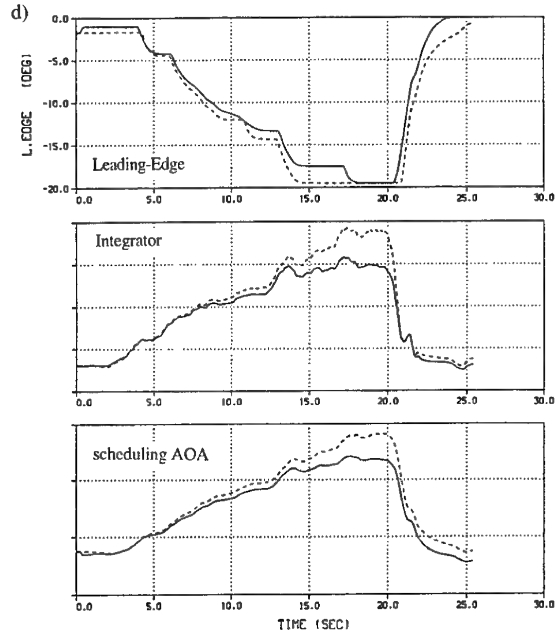


Fig. 6 Results of Flight Dynamics Simulation Check

3.2 Low Order Equivalent System (LOES) Analysis

The illustration of the LOES analysis will be given with a pitch 3211 manoeuvre. Fig. 7a gives the time history of the stick input. The signal has been filtered with a non-recursive low pass filter in order to improve the fidelity of the analysis result. Filtered and unfiltered signal are given in Fig. 7a, the difference is hardly visible, nevertheless filtering has a significant influence on the results. Fig. 7b gives the system response, the solid line the filtered, measured pitch rate and the dashed line the LOES calculated response. For this example a very simple approach was choosen with only a 4th order transfer function for numerator and denominator. Nevertheless with this simple model already a very good agreement has been achieved. A summary of the resulting Eigenvalue evaluation is given in Fig. 8 for the Short Period of the longitudinal motion. The result is an indication of the already very good handling qualities of EF2000 in this early stage of development.

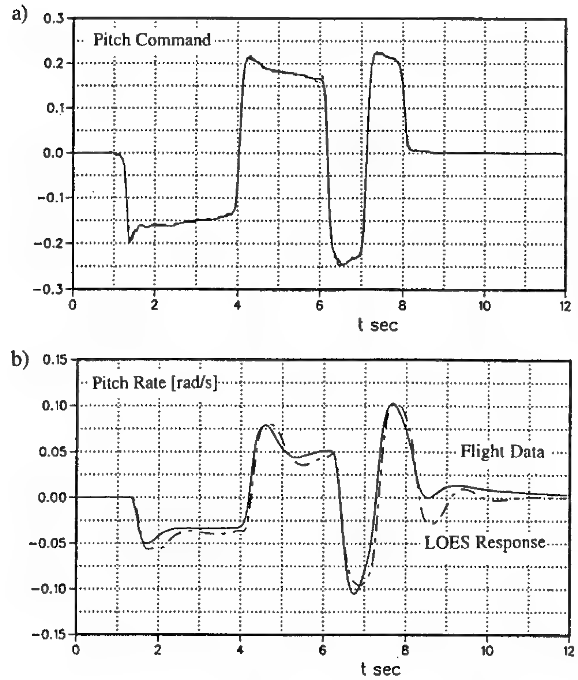


Fig. 7 Time Domain Results of Low Order Equivalent System Analysis

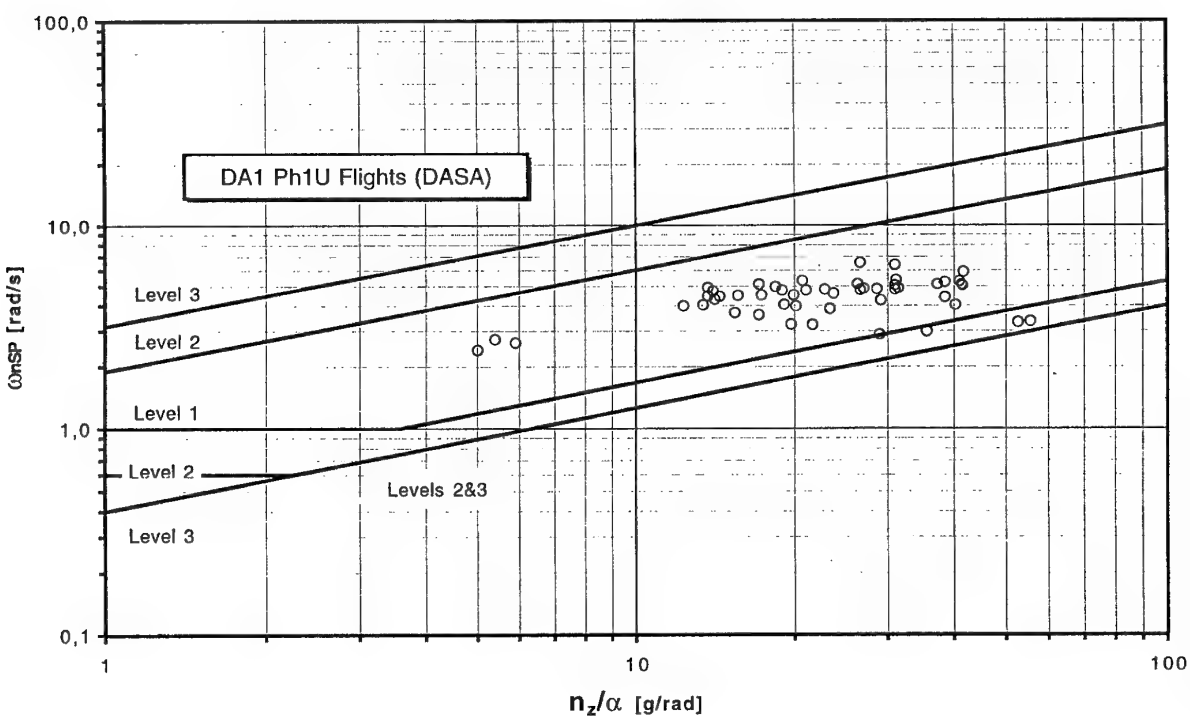


Fig. 8 Summary of Frequency Domain Results of Low Order Equivalent System Analysis (Short Period)

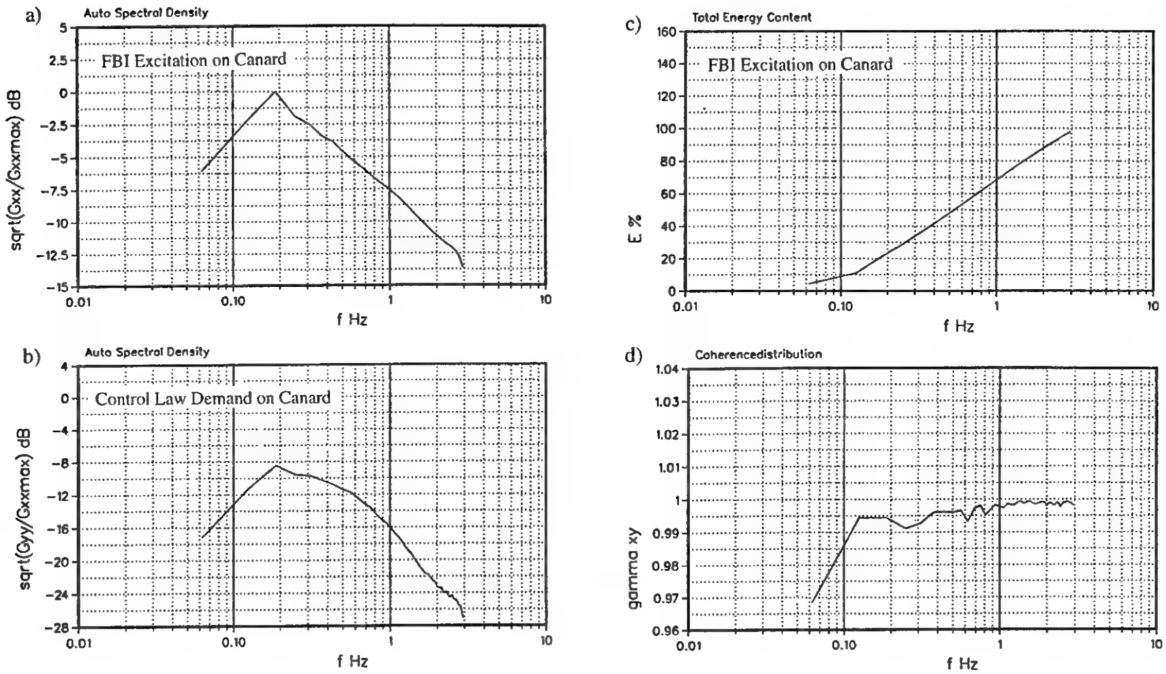


Fig. 9 Frequency Domain Analysis of FBI Excitation Signals

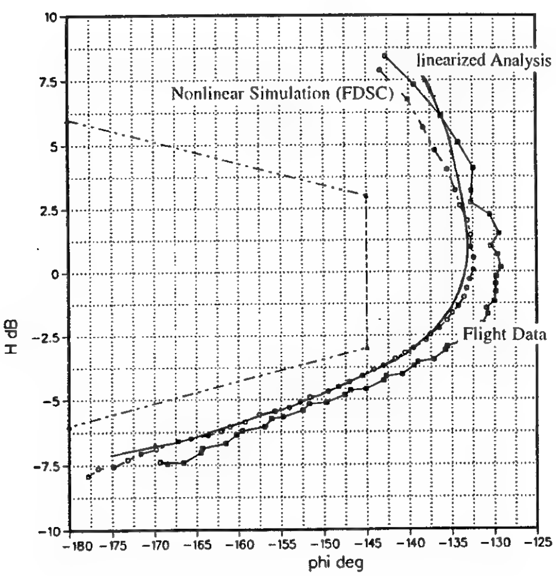


Fig. 10 Open Loop Stability Margins at the Bottleneck

3.3 Frequency Domain Analysis

3.3.1 Control Law Stability Evaluation

An example of FBI signal evaluation is given in Fig. 9 for FBI excitation at the canard command path, measured in flight on DA2, see also Fig. 3. Figs 9a and 9b show the spectra of the FBI excitation and the resulting control law demand, both spectra are normalised with the peak value of the FBI excitation spectrum. In addition Fig 9c gives the cumulation of energy in the excitation, also as a function of frequency, showing a linear distribution up to the maximum frequency at 3 Hz. The coherence function shown in Fig. 9d gives an indication on the validity of the resulting transfer function. It is the better the closer it gets to '1'. Finally Fig. 10 depicts the entire analysis result, showing the control law stability margin at the bottleneck, as derived with Eq. 6. Flight measured results have been derived from DA2 data with DASA analysis tools and are marked with the squares. Corresponding nonlinear simulation data have been produced with the described FDSC tool at DASA flight test and are marked with the circles, wheras the linearised analysis results come from DASA flight mechanics and are given as a solid line. The linearised data has been derived from an analytic control law model and not with Eq. 6. For this particular case a very good agreement between both predicted curves can be observed. A comparison between flight data and simulated data indicates that the predicted stability margin is closer to the stability boundary, thus indicating more stability in flight than with the model.

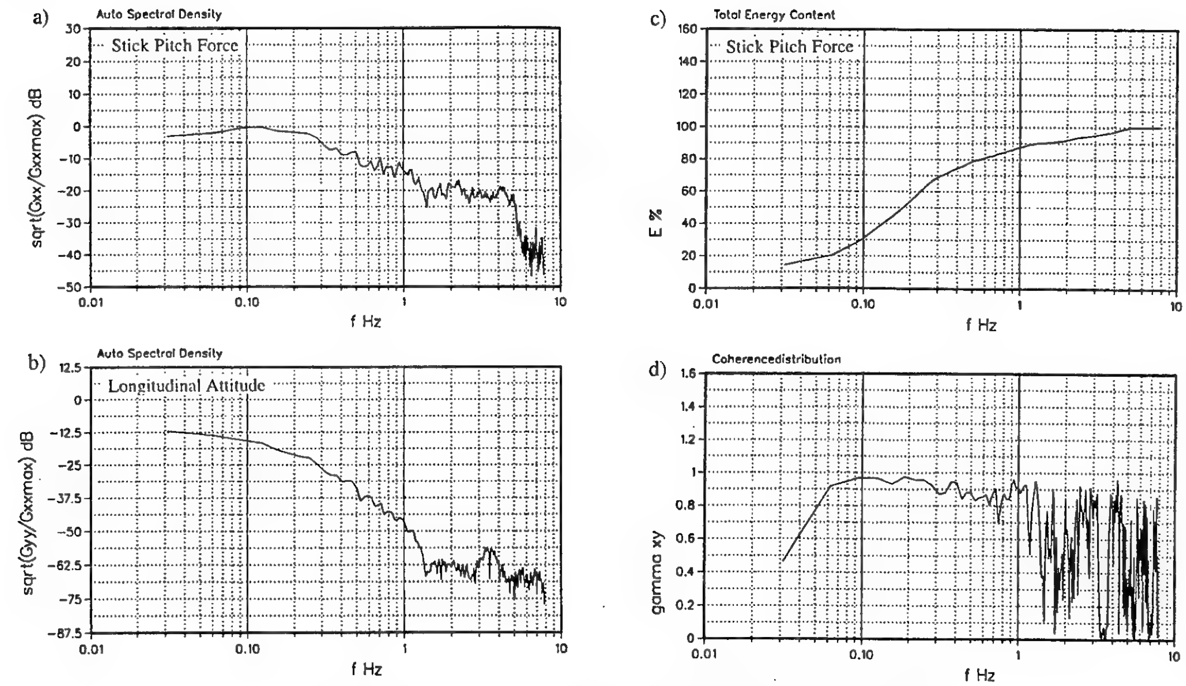


Fig. 11 Frequency Domain Analysis of Pilot Produced Frequency Sweep

3.3.2 Aircraft Pilot Coupling Evaluation

Aircraft pilot couplings criteria have been investigated in flight on DA1 with pilot produced frequency sweeps on the stick. This is a difficult task for the pilot especially for 'higher' frequencies, e.g. f>1.5 Hz. The resulting spectrum of the stick force signal is given in Fig. 11a. One can see that the distribution of energy is not as even as for the synthetic FBI excitation given in Fig. 9a. The spectrum of the corresponding system response, the aircraft's attitude, is given in Fig. 11b. The energy cumulation of the exciting stick force spectrum is given in Fig. 11c and one can easily see that most of the applied energy is already present for frequencies below 1 Hz. This has consequences on the quality of the resulting transfer function, which is already indicated in Fig. 11d with the results of the coherence distribution. For frequencies above 1 Hz only very poor coherence values can be observed. Nevertheless these results are tested against an aircraft pilot coupling criterion given by J. C. Gibson, Ref. 6. The result is given in Fig. 12. The resulting transfer function shows a very uneven trace, which has to be attributed to the above given arguments on energy cumulation and coherence distribution. For large phase lags the level 1 boundary is calculated from the slope of the measured transfer function. Since this is not so smooth, the slope calculation via numerical differentiation for this special case is questionable. Thus the result does not necessarily mean that the given boundary is hurt. It is expected at DASA flight test that these results will improve considerably once FBI signal excitation will also be available at the pilot's stick. In this context it should be noticed that the Gibson criterion is well suited for online analysis purposes.

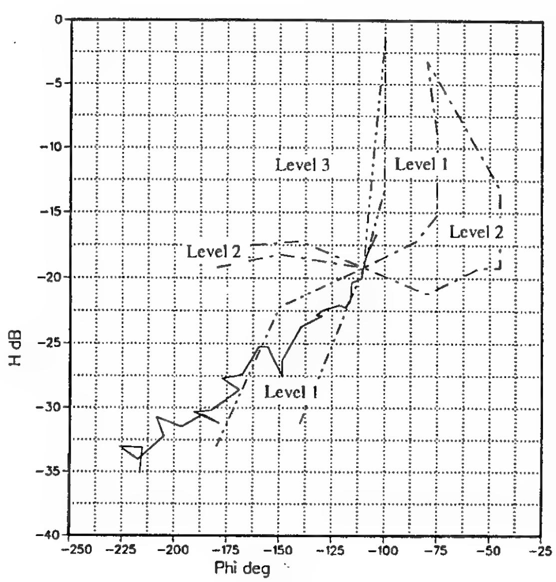


Fig. 12 Aircraft Pilot Coupling Criterion

3.4 Aerodynamic Parameter Identification (APID)

The presentation of results will be concluded with some typical APID results. Time histories of a pitch 3211 manoeuvre are given in Fig. 13. Fig. 13a gives a comparison of measured AOA (solid line) with the corresponding flightpath reconstruction result (dashed line). Figs 13b and c give the excitation via the control surfaces canard and symmetric flaperon, wheras Fig. 13d gives the measured load factor. Figs. 13e to h

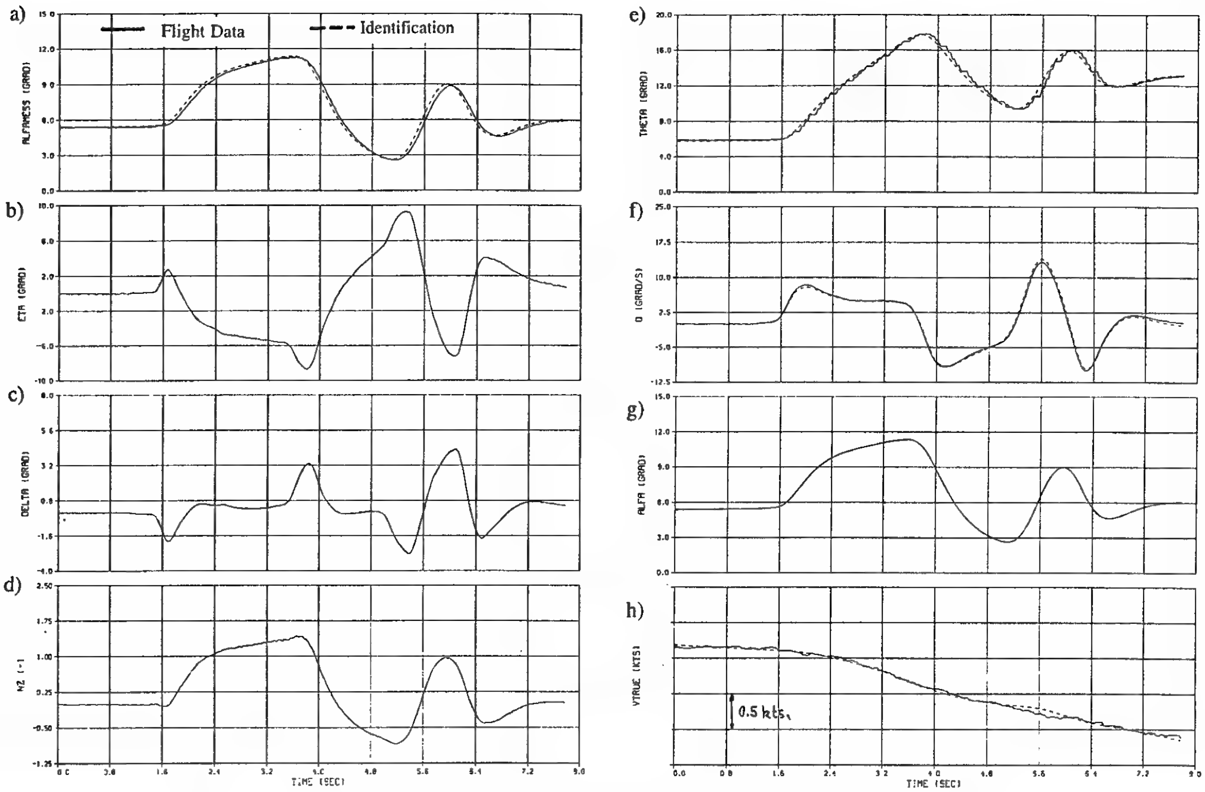


Fig. 13 Time Histories of Aerodynamic Parameter Identification Results

give the comparisons of measured state variables (solid lines) and 'identified' state variables (dashed lines). Identified state variables in this context means outcome of a simulation which uses as aerodynamic derivatives the results of the APID process. Good agreement of results in Figs. 13e to h is a necessary requirement for good APID results.

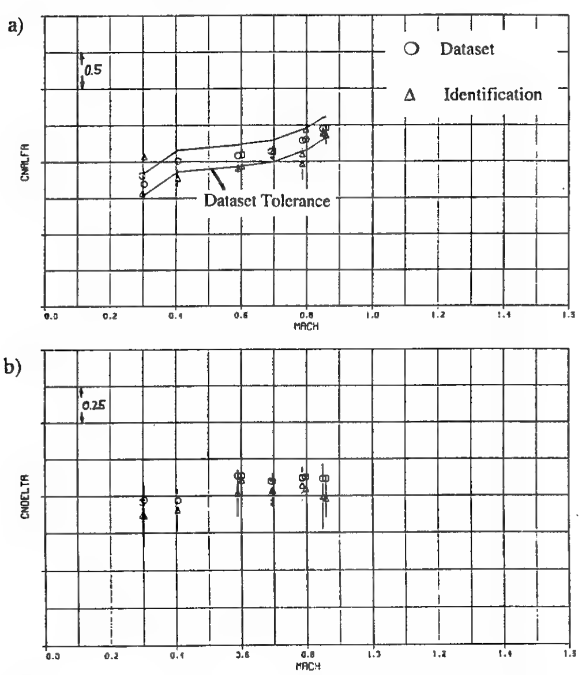


Fig. 14 Summary of Aerodynamic Parameter Identification of Longitudinal Aerodynamic Derivatives (Normal Force)

Some representative results for the longitudinal motion are given in Fig. 14 for the normal force coefficients $c_{N,\,alfa}$ (part a) and $c_{N,\,delta}$ (part b) and in Fig. 15 for the corresponding pitching moment derivatives, here also results for pitch damping c_{mq} (part c) are given. The figures give identified results as triangles together with 5σ deviation bounds as solid vertical lines. Predicted values as derived from the data set are given as circles, with respect to these circles data set tolerances are given as solid horizontal lines. The diagrammes reveal a very good coincidence between identification results and predictions, again indicating the high fidelity of the used model.

For these calculations the effectiveness of the canard was fixed due to a linear dependancy between canard and flaperon deflection. It is expected to improve this situation once the FBI will also be used for APID purposes, then the linear dependancy between canard and flaperon deflection can be disturbed, thus both effectivenesses could be identified.

Finally Fig. 16 gives a summary of further evaluations of the APID results. The identified derivatives have been used to calculate flight mechanical properties. As an example this figure gives the identified value of the stability margin during the tests.

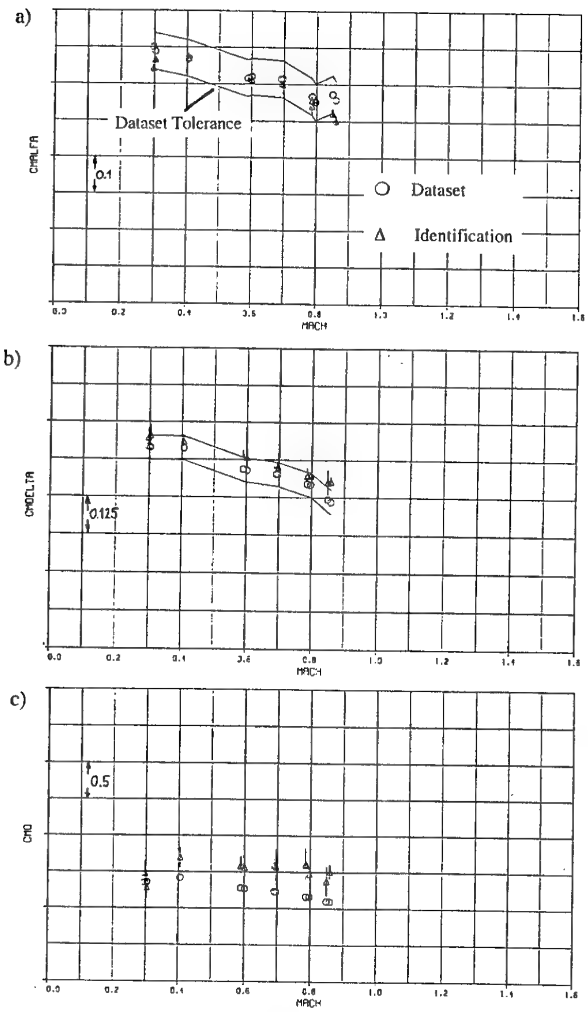


Fig. 15 Summary of Aerodynamic Parameter Identification of Longitudinal Aerodynamic Derivatives (Pitching Moment)

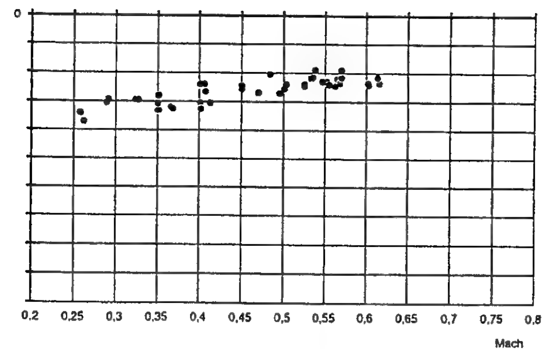


Fig. 16 Stability Margin as a Result of Aerodynamic Parameter Identification

4 Summary

EUROFIGHTER 2000 will be the future fighter aircraft for the air forces of Spain, Italy, United Kingdom and Germany. Currently the development flight test evaluation of this aircraft is under way. Flight test tasks are shared between partner companies. The present paper emphasises on analysis methods for flight mechanical and aerodynamical evaluation suitable for a very agile highly unstable fighter aircraft at DAIMLER-BENZ AEROSPACE flight test centre at Manching. Methods are summarised and illustrated with some representative results.

One major topic is the analysis of the augmented aircraft. Analysis methods in the time domain as simulation of flown manoeuvres and in the frequency domain as Z-transformation and Fourier analysis methods for system stability evaluations are presented. For the unaugmented aircraft DASA's aerodynamic parameter identification method is presented. It resembles a unique equation decoupling approach to cope with the problems arising from the analysis of unstable aircraft.

For the presented analysis methods some representative results are given. These results demonstrate the analysis capabilities of these methods. It is also shown that EF2000 flight testing can rely on an already high fidelity aerodynamic model. This gives confidence for the flight testing tasks.

5 References

1. A. V. Oppenheim, R. W. Schafer: Zeitdiskrete Signalverarbeitung, Oldenbourg Verlag, München, 1992.

2. A.P. Cherry: British Aerospace, Internal Report, 1995.

3. E. Plaetschke: Identifizierung instabiler flugmechanischer Systeme mit einem Ausgangsfehlerverfahren, Zeitschrift für Flugwissenschaften und Weltraumforschung 12 1988 (Heft4), 166-177.

4. H. Preissler, H. Schäufele: Equation Decoupling - A new Approach to the Aerodynamic Identification of Unstable Aircraft, J. o. Aircraft 28 1991(No. 2), 146-150.

5. H. Schäufele: Parameteridentifikation mit einem modifizierten Maximum-Likelihood-Verfahren, Fortschrittberichte der VDI Zeitschriften, Reihe 8 Nr. 40, 1981.

6. J. C. Gibson: Piloted Handling Qualities Design Criteria for Higher Order Flight Control Systems, AGARD CP-333, 1982, 4-1 to 4-15.

FLIGHT TESTING OF MANUAL FLIGHT CONTROL FUNCTIONS FOR A SMALL TRANSPORT AIRCRAFT (PROJECT ATTAS-SAFIR)

Thomas Heintsch
Robert Luckner
Daimler-Benz Aerospace Airbus GmbH
Flight Guidance and Control
P.O. Box 95 01 09
21111 Hamburg, Germany

Klaus-Uwe Hahn
Institut für Flugmechanik
DLR
Lilienthalplatz 7
38108 Braunschweig, Germany

1 Summary

In a technology programme DASA has developed flight control laws (FCL) for an electronic flight control system of a small transport aircraft (100-seater). In a cooperation between DASA and DLR, the flight control functions were tested on DLR's VFW614/ATTAS test aircraft.
This paper gives an overview of the flight control law development and testing within the SAFIR (Small Airliner Flight Control Law Investigation and Refinement) flight test project. Design objectives of the flight control system for the 100-seater are reviewed, a system overview is given, the flight control law functions are briefly explained and the development process is described. The testing procedure comprises the SAFIR experiment integration into the ATTAS test system, the definition of the flight tasks, the flight testing and the evaluation of the flight test results.

2 Nomenclature

AOA	angle of attack
ATTAS	Advanced Technologies Testing Aircraft System
CASE	computer aided software engineering
DASA	Daimler-Benz Aerospace Airbus
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
EFCS	Electronic Flight Control System
ERR	Experimental and Control Computer (Experimental- und Regelrechner
FBW	fly by wire
FCL	flight control law
FCLC	Flight Control Law Computer
ILS	Instrument Landing System
M_{MO}	maximum operational Mach number
ND	Navigation Display
n_z	normal load factor
PFD	Primary Flight Display
RA	radio altimeter
SAFIR	Small Airliner Flight Control Law Investigation and Refinement
t	time
V_{CAS}	calibrated airspeed
$V_{\alpha lim}$	airspeed corresponding to α_{lim}
V_{MO}	maximum operational speed
$V_{\alpha prot}$	airspeed corresponding to α_{prot}
ZKR	Central Communication Computer (Zentraler Kommunikationsrechner)
α	angle of attack
γ	flight path angle
η	elevator deflection
θ	pitch attitude
ξ_R	aileron deflection (right hand)
Φ	bank angle
Φ	roll attitude rate

3 Introduction

Today, the application of fly by wire (FBW) technology to civil transport aircraft can be considered as the state of the art. Airbus Industrie was the first aircraft manufacturer to make use of this technology. Now a family consisting of five aircraft types (A319, A320, A321, A330, A340) is under production with 700 aircraft in service and 1300 orders (as at April 1996). The projection for the end of the century is that more than 1000 aircraft with EFCS will be flying and more than 10,000 pilots will have been trained. Taking this scenario into account and considering advantages and disadvantages of mechanical and electronic FCL systems DASA decided to use fly-

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

by-wire technology for its 100-seater project. Facing the project it was clear that design to cost would be a major challenge in EFCS development for such a small transport aircraft because the price of a commercial transport is related to the number of passenger seats, and can be given in terms of dollars per seat. As the price of avionic systems - such as EFCS - is virtually independent of aircraft capacity (assuming equivalent performance), the EFCS share in the specific cost of a 100-seater is nearly twice that of a 200-seater [1].

4 Flight Control System

4.1 Design Objectives

Minimum requirements for EFCS are defined by the certification regulations. Additional requirements come from market analysis and the perceptible progress of technology. Due to the unfavorably high share that EFCS contributes to the specific cost of a small transport aircraft, cost efficiency becomes the dominating factor in the EFCS design process. Flight control law design, as part of EFCS design, will influence:

- system development costs;
- aircraft qualification costs (stability and control);
- crew training costs;
- modification costs.

A cost-effective FCL approach must be simple, based on proven techniques that are accepted by the certification authorities, and should use familiar standard control functions in order to reduce crew training costs.

Special attention has to be paid to the software design process as modern design tools (CASE tools) may significantly reduce software design costs if properly applied.

With a scalable controller structure and modular design, DASA's FCL approach is not exclusively targeted to a specific aircraft but can be adapted to other aircraft types.

4.2 System Overview

The principle of the 100-seater EFCS is shown in Fig. 1 as a block diagram. All flight control surfaces are electrically controlled and hydraulically activated (Fig. 2). The stabilizer and the rudder have an additional mechanical link as a back-up.

In the cockpit, we find:

- two side sticks for pitch and roll control (not mechanically coupled);
- two pair of pedals for yaw control (rigidly interconnected);
- a rudder trim switch;
- two handwheels for control of the trimmable horizontal stabilizer;
- two priority push buttons;
- a speed brake lever;
- a slat/flap lever;
- a thrust lever.

Sensors that measure feedback parameters include:

- three air data/inertial reference units;
- two radio altimeters;
- accelerometers.

Additional sensors necessary e.g. for ground spoiler logic are:

- wheel tachometer;
- landing gear compressed switch;
- thrust lever position sensor.

For flight parameter indication, the primary flight display is used. Two lamps indicate priority if requested by one of the pilots. System status and failure conditions are displayed on the Engine Display and the System Display, respectively.

4.3 Flight Control Functions

The FCLs provide both primary control functions (pitch, roll and yaw) and secondary control functions (slat/flap, airbrake and ground spoiler). In addition, they calculate operational and limiting speeds as well as parameters dealing with the flight envelope protections, and display these on the PFD. Generally, the functional design is aimed at crew commonality with AIRBUS aircraft; all functions and the man-machine interface are similar in order to reduce the cost of transition training. However, everything that is hidden to the pilot - i.e. systems and software - is realized differently.

For normal operation (that is, as long as no systems have been degraded due to failures) three modes are necessary:

- ground mode;
- inflight mode;
- flare mode.

The transition from one mode to the other has to be smooth, with no adverse effect on the pilot's ability to control the aircraft.

The normal laws provide complete flight envelope protection as follows (see Fig. 3):

- load factor limitation;
- high angle of attack protection;
- high speed protection;
- pitch attitude protection;
- bank angle protection.

Envelope protections are designed to prevent specified boundaries from being exceeded. They assist the pilot by initiating corrective action if necessary, but they do not assume the pilot's decision-making role or his responsibility for safe

flight. A more detailed description of the protection functions is given in [4].
In the event of multiple system failures, the FCLs shed protection functions or degrade from the normal law to the direct law, according to the number and nature of the successive failures.

Inflight Mode
Pitch Normal Law. The pitch normal law is a load factor demand law with automatic trim function. At low speed, load factor is blended with pitch rate. With the side stick at neutral during level flight, this law provides short-term flight path stability and compensates for turbulence. Turn compensation is provided up to 33° bank angle.
Roll Normal Law. Roll normal law is a roll rate demand/bank angle hold law. The roll rate demand is proportional to side stick deflection and limited to ±15°/s. Bank angle hold is provided up to ±33° bank with automatic turn coordination and turn compensation. This allows turns to be flown in normal airline operations without pitch input.
Yaw Normal Law. The yaw normal law is a direct control-to-surface law (pedals to rudder) with maximum deflections limited by the rudder travel limitation function. Additionally,
- yaw damping,
- turn coordination, and
- automatic trim in case of engine failure

is provided.

Flare Mode
In order to provide a conventional flare (where the pilot has to pull the side stick back progressively to achieve a gently increasing pitch attitude during flare), longitudinal control changes at 50 ft from inflight to flare mode:
- automatic trim is deactivated;
- a modified normal law with load factor and pitch rate feedback is activated.

Ground Mode
On the ground, side stick deflections correspond directly to elevator, aileron and roll spoiler deflections. There is no automatic pitch trim. After takeoff, the flight mode is progressively blended in.

Direct Laws
In case of system or sensor failures which prohibit the correct performance of the normal laws, FCL's are degraded to the direct laws. The direct laws are direct control-to-surface laws without any protections and a rough scaled set of feedforward gains.

5 FCL Development Process

Development of a system is an iterative process, and several different models are used to describe it. In the V-Model, the analytical steps are listed on the left leg, and the steps towards a synthesis on the right leg. The links between them define verification and validation activities on different levels (see Fig. 4). FCL development is part of the system development process, and a rational and methodical approach can reduce development costs significantly. The elements
- CASE Tool: HOSTESS
- test facilities: development flight simulator
- flight test: VFW614/ATTAS flying test bed.

play a keyrole in the optimization of the FCL development process (Fig. 5).

5.1 CASE Tool HOSTESS

Based on experience (e.g. with the center of gravity control computer for A300 and A310), DASA has developed the CASE tool HOSTESS (High Order Structuring Tool for Embedded System Software). Its goal is to standardize software specification, to automate the coding process, to provide automatic checks and testing, to improve software documentation, and to facilitate configuration management. HOSTESS provides:
- software specification using a graphical block diagram language in conjunction with a symbol library and assembly rules which are easily understood by electronics and automation engineers;
- a consistency check of each module;
- automatic coding with different code generators (FORTRAN, ADA, etc.);
- a hierarchical software structure.

The benefits are:
- a reduction in coding errors;
- the automatization of routine activities during the software development cycle, especially for modifications;
- standard, unambiguous software specification.

5.2 Development Flight Simulator

Tests on the flight simulator are conducted in order to validate the FCL functions and their reconfiguration in a real-time environment. In particular, the transitions from one mode to another in combination with different pilot inputs and various flight states can only be investigated in real time.
The DASA flight simulator facility has been continously upgraded over the past years and now features:
- high fidelity simulation models;
- generic 100-seater cockpit (sidestick,

6 displays, etc.);
- visual system;
- sound system;
- data acquisition and analysis.

More than 1000 simulator flight hours have been "flown" with engineers and various test and airline pilots at the controls.

An ethernet data link between the development workstations where the FCL's are specified and coded by means of "HOSTESS" and the flight simulation computer allowed a highly efficient development process.

6 ATTAS Flight Test Facility

6.1 ATTAS Test Aircraft

In the early 80's the flying simulator and demonstrator aircraft ATTAS (Advanced Technologies Testing Aircraft System) was developed as a testbed by DLR and DASA (former MBB) supported by the German Ministry of Research and Technology. The system architecture of the ATTAS in-flight simulator is outlined in several papers [2,3,5]. ATTAS is based on a VFW614, twin-turbofan, short haul 44-passenger aircraft (Fig. 6).

The aircraft is equipped with a complete flight test instrumentation. The heart of ATTAS testbed is the experimental fly-by-wire system (20ms cycle time) with interfaces to aircraft systems (ARINC 429, MIL-Bus 1553B, etc.). All on board computers are of MIL-specified LORAL/ROLM types (MSE 14 and HAWK 32). 1.4 MFLOPS are available for experimental functions on the HAWK/32 32-bit computer with 8 MB of memory. The network is based on a ring structured serial fibre optical bus system.

In flight test ATTAS can be operated in three principal modes:
- basic mode: VFW614 standard mechanical flight control;
- FBW mode: FBW system active as a direct link;
- SIM mode: FBW system active with user-defined functions.

The aircraft is operated by two pilots, an experimental and a safety pilot. The experimental pilot is sitting on the left-hand side. His side of the cockpit is equipped with a side stick controller and two displays (PFD and ND, Fig. 7). He controls the aircraft via the FBW computer system. The FBW actuator inputs are mechanically fed back to the safety pilot's control column on the right-hand side which is mechanically linked to all controls. This feed back function enables him to monitor the movement of the control surfaces. This is an important safety aspect, because he can evaluate, whether the inputs are adequate to the flight task. He can disengage the FBW control system by switching off or by overriding the control actuators. The actuators are force limited to avoid structural damages of the basic aircraft. For safety reasons the VFW614 flight envelope is restricted in the FBW and SIM modes: a maximum cruising altitude of 25000 ft, maximum cruising speed of 288 kts (0.65 Mach) calibrated airspeed (CAS) and a rather low landing speed of about 100 kts is adequate for a transport aircraft flight regime representation. The high maneuverability is adequate for a broad spectrum of flight experiments [6]. Fig. 8 illustrates the ATTAS FBW envelope available for the SAFIR flights.

6.2 ATTAS System Simulator

For testing and training on ground, DLR has build up the ATTAS system simulator which is a one by one duplicate of the ATTAS flight test system. It consists of:
- a fixed base flight simulator cockpit;
- a simulation computer with a VFW614 simulation model;
- the original ATTAS data processing system.

The ATTAS system simulator was used for the verification of the FCL software that had been developed in DASA's flight simulator, the adaption to the ATTAS real world system, the experimental check out and the pilot's familiarization and test training.

7 SAFIR Project

In April 1993 DASA and DLR launched the SAFIR project for the investigation of flight control laws developed by DASA for a 100-seater aircraft. Within this project FCLs were validated, demonstrated and evaluated in flight with DLR's VFW614/ATTAS as test aircraft. It was decided to adapt DASA's FCLs to the VFW614's flight dynamics, instead of using ATTAS as an inflight simulator for the 100-seater with the original 100-seater FCLs.

Not more than half a year later, in October 1993 the first flight was carried out. The aim of the first test campaign **(SAFIR 1)** was to evaluate the functionality and performance of the FCLs within the whole flight envelope. The test campaign comprised 6 test flights. In 130 single tests all functions of the normal laws and protection laws were investigated. Special points of interest were control accuracy of the FCLs, handling qualities and the transition between the different operating modes.

In **SAFIR 2**, the second project phase the emphasis was laid on the investigation of system aspects. For that purpose FCLs were doubled in two dissimilar software languages (FORTRAN,

ADA) to be implemented in a command and a monitor lane. Based on the same block diagram specification the design tool HOSTESS automatically generated the two software packages. This configuration enabled the investigation of:
- monitoring between command and monitor lane;
- data consolidation between command and monitor lane;
- degradation from normal law to direct law.

Within the SAFIR 2 campaign 6 test flights with 175 single tests carried out in the years 1995 and 1996 by several test pilot's and an airline pilot having different flight experience.
The total flight time for the whole SAFIR project was 32 hours with 305 single tests (Tab. 1). The evaluation of the flight test results lead to modifications in the FCLs which always were considered in the software for the next test flight. All in all 110 modifications were tested in 9 different software versions.

7.1 Experimental Set-Up

7.1.1 ATTAS Test System Configuration

In preparation of the flight tests the FCL software had to be implemented in the ATTAS data processing system. A software interface had to be realized
- that provided the input signals for the FCL software module in the appropriate format,
- that connected the FCL output signals to control surfaces and displays.

Additionally adaptions were necessary concerning:
- data recording of user defined signals;
- modification of the side stick force characteristic;
- generation of automatic test functions for FCL input (e.g. synthetic side stick inputs);
- assignment and interpretation of FCL control signals (e.g. activation of test functions, switching between modes);
- Modifications of PFD and ND to indicate test relevant signals (FCL messages, characteristic speeds, synthtic ILS signal).

7.1.2 Software Implementation (SAFIR 1)

In the first project phase the FCLs were computed on the *Experimental and Control Computer* (ERR) of ATTAS. The software was transferred via floppy disc and copied one by one. With a configured ATTAS test system no additional modifications were necessary for implementing a new software on the assumption of an identical FCL interface.
An essential stability criterion of a flight control system is the total time delay (time between pilot's input and control surface movement). For the ATTAS test system it can be determined by the fifthfold of the ERR cycle time. With a value of 35ms the time delay was 175ms.

7.1.3 Hardware Modifications (SAFIR 2)

Due to the doubling of FCL software for command and monitor lane in the second project phase, the performance of the Experimental and Control Computer was exceeded. Therefore a high performance flight worthy Flight Control Law Computer (FCLC) a HARRIS Night Hawk 4401 has been installed in the ATTAS test system and linked to the *Central Communication Computer* (ZKR) (Fig. 9). The HARRIS computer (1 CPU VME-bus board with a MOTOROLA 88100 processor) computes the command and monitor lanes of the flight control laws within a cycle of 20ms. For the communication between FCLC and ZKR six ARINC 429 highspeed lanes (three input lanes, three output lanes) were provided (Fig. 10).
The installation of the FCLC required major software modifications both to implement the FCL software into the FCLC including monitoring and data consolidation functions and to link the FCLC to the ATTAS test system. With a data transmission time of 80ms (ZKR->FCLC->ZKR) the total time delay was 180ms (5*20ms for ATTAS test system) which is in the same magnitude as for SAFIR 1.

7.2 Flight Tasks Definition

Flight tasks for the validation of FCL functions within the "normal flight envelope" comprise side stick or pedal inputs in order to check:
- the aircraft's dynamic reaction in terms of time constant, damping behaviour, etc.;
- the ability of the normal FCLs to hold flight path angle and bank angle after side stick release;
- the correct operation of functions like turn coordination, turn compensation, automatic pitch trim, one engine out compensation.

Checking the performance of the flight envelope protections special attention is paid to:
- a smooth transition between normal law and protection;
- adequate maneuverability up to the target limits without overshoot.

For investigations of handling quality, a special maneuver (Fig. 11) was defined by DLR, in which the pilot flew a vertical pattern in the normal law, running into the bank angle protection during the 45° bank turn. For evaluation a pilot questionnaire was prepared (Fig. 12) asking for Cooper/-

Harper ratings of specific tasks during the maneuver.
Handling qualities as classified by the pilots were Level 1 within the normal flight control laws and -as expected- Level 2 within the bank angle protection, where the pilot had to stabilize the bank angle with the side stick (bank angle command) and comfort functions like turn compensation or turn coordination were deactivated.
The FCL performance in normal airline operation was investigated with typical maneuvers like:

- ILS approach;
- heading changes in climb/descent;
- step climb/descent with turns.

As the minimum altitude in FBW and SIM mode was restricted to 500ft, the ILS approaches had to be carried out in higher altitudes. For that purpose a synthetic ILS signal was generated, with localizer and glideslope deviations indicated on the PFD and ND (Fig. 13). The raw data ILS approach (no flight director) included localizer and glideslope intercept with a 10NM final approach. The synthetic ILS signal was activated via a switch operated by the flight test engineer.
To ensure a maximum of efficiency flight tests had to be carefully prepared. The test flights consisted of single flight tasks, each specified on a test procedure card (Fig. 14). The test cards contained detailed information about the aircraft's initial flight condition and the test sequence in terms of a verbal description of every single step. Pilot marks indicate begin and end of test for later identification. Cooper/Harper ratings and pilot comments were noted.
In advance of the test flight the complete test program was flown in the ATTAS system simulator with the purposes:

- final check of the FCL software;
- familiarization of the test pilot with the FCLs;
- training of the test procedures;
- optimization of the test programme.

Typically a test flight comprised between 18 and 36 single tests within about 2.5h-3h of flight time.

8 Flight Testing

8.1 Execution of Experiment

On board of ATTAS the DLR flight test crew was supported by DASA engineers, a flight test engineer and two FCL experts. The flight test engineer read out the test procedure cards and was responsible for the correct processing of the flight tasks. The FCL experts monitored the tests by means of a quick-look terminal which displayed test relevant signals online in numerical or graphical form.
By a set of 15 switches online modifications in the test software during the flight tests was possible. Setting of the switches was defined in a switch declaration list (Fig. 15). The switches were used for e.g:

- degradation from normal law to direct law;
- activation of the synthetic ILS signal;
- variations of side stick characteristic (deadspace and slope);
- activation of synthetic side stick step inputs.

The evaluation of the flight began immediately after the flight in the debriefing with a complete walk through the test procedure cards. The pilot comments were discussed including comparisons between flight simulator and flight test and notation of unexpected events during the flight. A first analysis was possible a few hours after the flight when the first test results were available from the DLR data processing system. These overview time histories of the relevant experiment sequences were plotted on three "wall-papers" (six papers for SAFIR 2), each representing up to 33 flight test parameter. Although of limited resolution (due to data reduction) the time histories were well suited for an assessment and often most of the 'open items' of the debriefing could be explained already in this early state of evaluation.
The first two test flights of the SAFIR 1 programme were dedicated to adjusting the FCLs to the ATTAS FBW system as to:

- sensor calibration and filtering;
- fine tuning of gains (e.g. turn coordination at low speed);
- adaption to the force reduced FBW actuators.

Minor software modifications became necessary. During the following flight tests the ATTAS adapted FCLs were tested within the whole flight envelope and showed good quality without any malfunctions. Modifications in the flight control software were necessary only in order to optimize gains and transitions between the different operating modes.
As an important result, the FCL development methodology proved to be efficient. Software modifications could be performed within a short time, reliably and accurately, using HOSTESS. Simulator tests showed high fidelity with respect to the flight tests except for the well-known and accepted shortcomings: real-life/visual system disparity, motion, and pilot anxiety levels. Due to careful preparation flight tests were performed on high efficiency level.

8.2 Flight Test Results

From the whole number of single flight tests four representative time histories are presented.

Bank Angle Protection

Fig. 16 shows the results of a maneuver for testing roll control. Pilot's task was a doublette of side stick maximum roll commands (LH, RH) without rudder and thrust inputs. Up to 33° bank angle, roll control is a roll rate command/bank angle hold function with a maximum of 15°/s commanded roll rate, which in the test is achieved just when reaching the -33° bank angle. Beyond -33°, bank angle protection with a bank angle command becomes active limiting the maximum bank angle to -45° (according to ATTAS flight envelope). The transition between roll rate command and bank angle command is smooth, the maximum bank angle is kept without overshoot. During the following bank to bank maneuver the aircraft rotates with maximum admissible roll rate of 15°/s up to +45° bank. The test sequence ends with a side stick release which lets the aircraft automatically roll back to 33° bank angle. Here the bank angle hold function stabilizes the constant turn as required.

High AOA Protection

The operation of high AOA protection is illustrated in Fig. 17. The pilot decelerates the aircraft by reducing thrust to idle without side stick input. At $t \approx 20$s, AOA reaches α_{prot} and the high AOA protection is activated resulting in a transition from n_z-command to α-command (stick to neutral commands α_{prot}, full back stick commands maximum admissible angle-of-attack α_{lim} which is 2°-3° beneath the stall-AOA). The aircraft stabilizes α_{prot} with a reduction in flight path angle due to thrust setting. The aircraft descends with stabilized $\alpha = \alpha_{prot}$ and $V_{CAS} = V_{\alpha prot}$. At $t \approx 85$s the pilot commands α_{lim} by pulling the side stick full back. Despite this step input the nose up reaction is smooth. α_{lim} is reached without overshoot. Side stick release let's the aircraft automatically stabilize α_{prot} again.

High AOA Protection (dynamic)

Fig. 18 shows that the high AOA protection operates precisely even in dynamic maneuvers, such as the side stick full back step input at $V_{CAS} = 180$kts. The aircraft reacts with a $\Delta n_z = 0.8$g pitch up movement up to 22° pitch attitude. The high AOA protection counters this dynamic nose-up maneuver with a 4° nose down elevator command. The aircraft stabilizes at $\alpha = \alpha_{lim}$ and $V_{CAS} = V_{\alpha lim}$. In neither of the high AOA protection tests the maximum angle-of-attack α_{lim} has been exceeded.

High Speed Protection

The high speed protection limits the maximum speed beyond V_{MO} ($V_{MO,ATTAS} = 255$kts). For a sudden full nose down command the aircraft must not exceed $V_{MO} + 30$kts ($M_{MO} + 0.07$), for a long term full nose down command, maximum airspeed is limited to $V_{MO} + 16$kts ($M_{MO} + 0.04$).

The time histories in Fig. 19 show the aircraft reaction on a sudden full nose down command initiated at a speed of $V_{CAS} = 225$kts. The aircraft rapidly pitches down and is stabilized at $\Theta = -15°$ by the pitch attitude protection. With a speed advance of 10kts due to pitch attitude, side stick command and horizontal acceleration, high speed protection is activated at $V_{CAS} \approx 240$kts.
With a combination of side stick nose down command reduction and nose up load factor command a smooth intercept maneuver is performed. The aircraft achieves a maximum speed of 285kts ($\approx V_{MO} + 30$kts) and then slowly decelerates towards $V_{MO} + 16$kts until side stick pitch command is released.
The pitch behaviour fullfills the requirements precisely although additionally a turn maneuver with alternating full side stick roll inputs is performed. Due to a bank angle limitation of 30° in High Speed Protection the aircraft rolls up to ±30°bank angle without overshoot. After side stick roll command release wings levelled out again as required (positive spiral stability).
As with these examples, all other FCL functions have been tested successfully. Pilots judged the inflight results to be consistent with the simulator results despite transition processes due to mode switching, particularly from the n_z-command to the α-command. This transition, which is sensitive to pitch rate and load factor cues, could only be optimized by means of flight testing.

9 Conclusions

A comprehensive set of manual flight control functions is being developed for implementation in an EFCS for a small transport aircraft on the premise of an AIRBUS similar functional design. The FCLs have been validated by flight simulator tests and have been favorably received by test and airline pilots.
For inflight tests, they were adapted to the dynamics and operational constraints of the DLR's VFW614/ATTAS flying test bed. Supported by a small but well trained flight crew ATTAS was ideally suited to offer the possibility of using its FBW capability to investigate and operate the (uncertified) experimental FCL software. It permitted flight tests in a real world environment with a short term experiment preparation at low cost and low risks.
Within the SAFIR project performed by a joint DASA/DLR team, a very effective and well organized infrastructure has been built up between the partners. In more than 300 single flight tasks all FCL functions were investigated in detail with different test and airline pilots. The flight test results showed high precision of the FCL perfor-

mance with respect to the requirements. The handling qualities for airline typical operations were rated as Level 1.

10 Acknowledgements

The authors would like to thank their collegues from DASA Airbus in Hamburg and DLR in Braunschweig, who contributed to the success of the SAFIR flight test campaign.

11 References

[1] H. Seidel:
Cockpit and Avionics for a Small Jet Transport Aircraft
ERA Technology Ltd. Avionics Conference, London, December 1992

[2] D. Hanke, H.-H. Lange:
Flight Evaluation of the ATTAS Digital Fly-by-Wire/Light Flight Control System
Vortrag ICAS-88-3.6.1
Jerusalem, Aug./Sept. 1988

[3] D. Hanke, J.-M. Bauschat, H.-H. Lange, H. Heutger:
In-Flight-Simulator ATTAS-System Design and Capabilities
DGLR Symposium "In-Flight Simulation for the 90's
DGLR Conference Proceedings 91-05
Braunschweig, July 1990

[4] R. Luckner, T. Heintsch
Development of Manual Flight Control Functions for a Small Transport Aircraft
Vortrag ICAS-94-7.6.1,
Anaheim, Sept. 1994

[5] J.-M. Bauschat, H.-H. Lange
ATTAS and its Contributions to System Design and In-Flight Simulation
International Conference Aircraft Flight Safety, Conference Proceedings,
pp. 403-413, 1993

[6] J.J. Buchholz, J.-M. Bauschat, K.-U. Hahn, H.J. Pausder
ATTAS & ATTHES In-Flight Simulators
Flight Vehicle Integration Panel Symposium, AGARD CP 577,
Braunschweig, May 1995

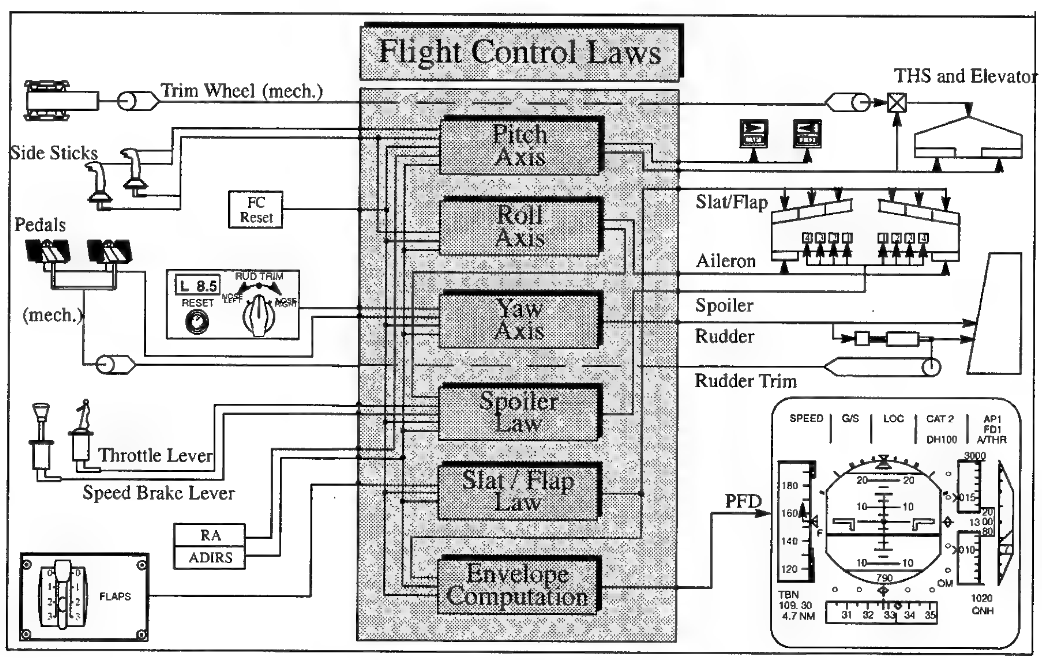


Fig. 1: EFCS Block Diagram

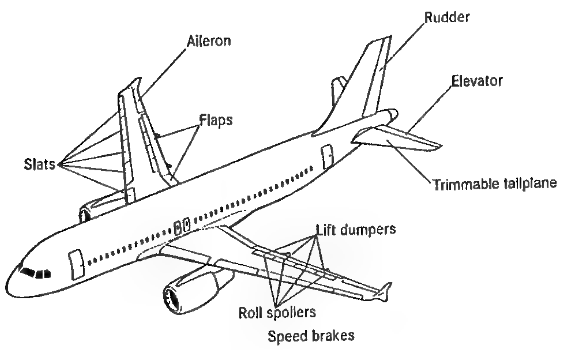


Fig. 2: Control Surfaces

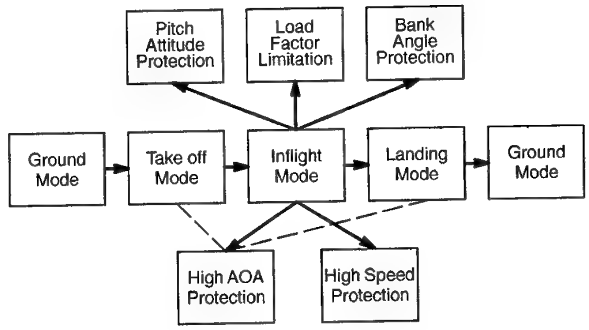


Fig. 3: Normal Flight Control Law Modes

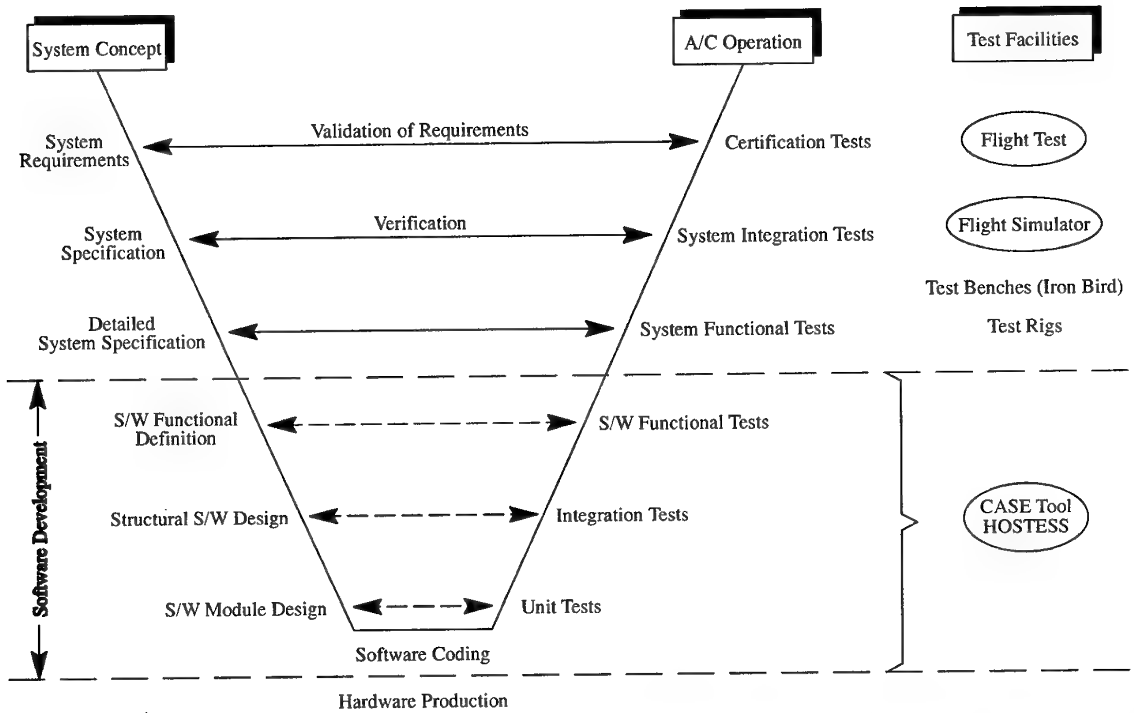


Fig. 4: V-Model for FCL Development Process

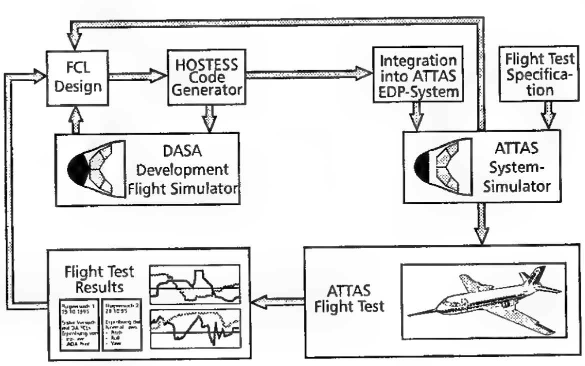


Fig. 5: Flight Control Law Development Process

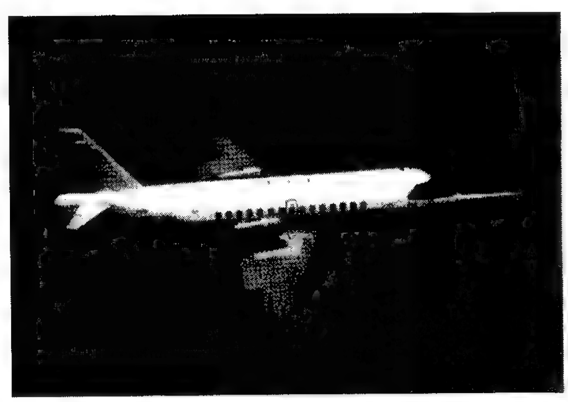


Fig. 6: VFW614/ATTAS Test Aircraft

Fig. 7: VFW614/ATTAS Expermental Cockpit

EFCS flight no.	date	flight time	total flight time	single tests	software version
1	19.10.1993	2:40	2:40	27	1.1
2	28.10.1993	2:55	5:35	31	1.2
3	09.11.1993	2:40	8:15	20	1.3
4	23.11.1993	2:30	10:45	18	1.4
5	23.11.1993	2:05	12:50	15	1.4
6	15.07.1994	2:24	15:14	19	1.5
7	13.03.1995	2:57	18:11	31	2.1
8	27.04.1995	2:56	21:07	32	2.2
9	03.05.1995	2:34	23:41	36	2.2
10	12.06.1995	2:51	26:32	32	2.3
11	20.06.1995	2:23	28:55	26	2.3
12	07.05.1996	3:05	32:00	18	2.4

Σ 305 single tests

Tab. 1: SAFIR Flight Test Overview

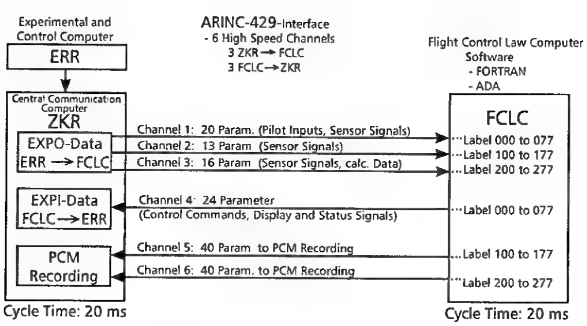


Fig. 10: Communication between ZKR and FCLC

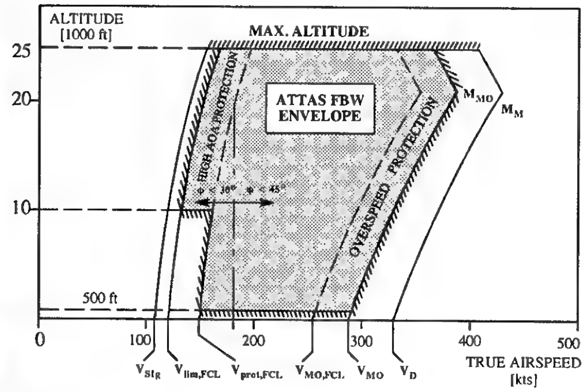


Fig. 8: ATTAS FBW Envelope

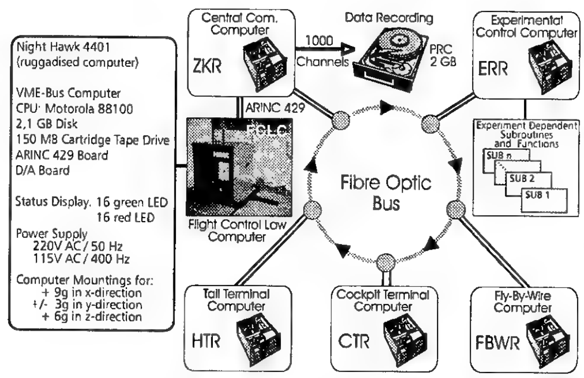


Fig. 9: FCLC Integration into ATTAS Test System

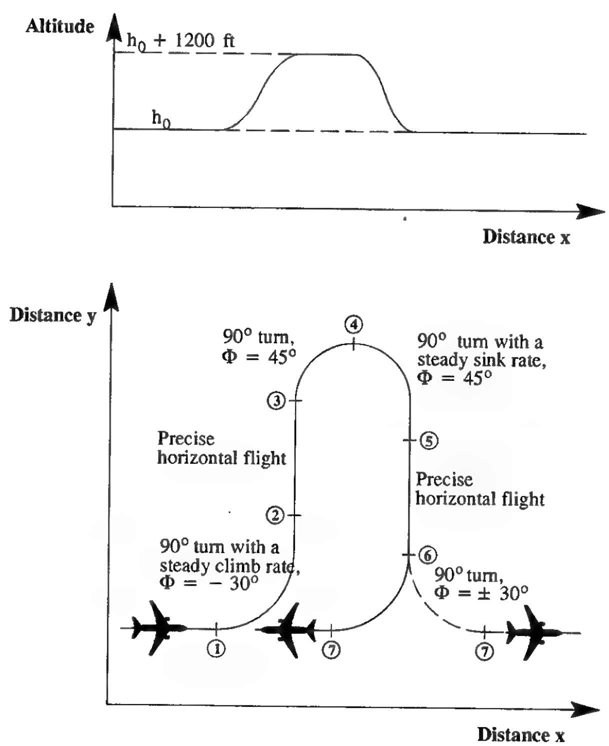
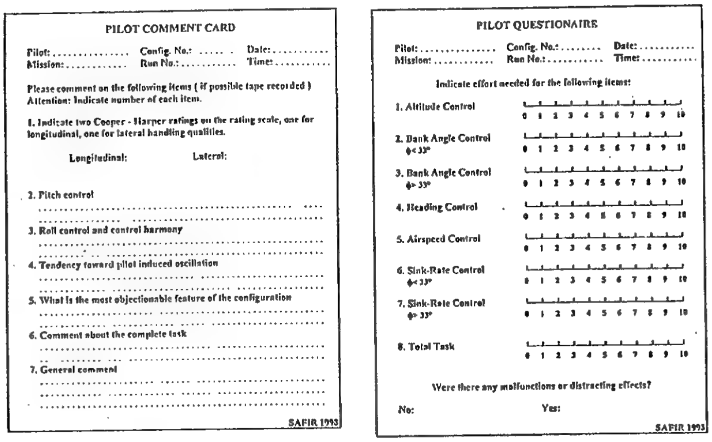


Fig. 11: SAFIR Maneuver



PILOT COMMENT CARD

Pilot: .... Config. No.: ..... Date: ....
Mission: .... Run No.: .... Time: ....

Please comment on the following items (if possible tape recorded)
Attention: Indicate number of each item.

1. Indicate two Cooper - Harper ratings on the rating scale, one for longitudinal, one for lateral handling qualities.

Longitudinal: Lateral:

2. Pitch control
3. Roll control and control harmony
4. Tendency toward pilot induced oscillation
5. What is the most objectionable feature of the configuration
6. Comment about the complete task
7. General comment

SAFIR 1993

PILOT QUESTIONAIRE

Pilot: .... Config. No.: .... Date: ....
Mission: .... Run No.: .... Time: ....

Indicate effort needed for the following items:

1. Altitude Control 0 1 2 3 4 5 6 7 8 9 10
2. Bank Angle Control $\phi < 33°$ 0 1 2 3 4 5 6 7 8 9 10
3. Bank Angle Control $\phi > 33°$ 0 1 2 3 4 5 6 7 8 9 10
4. Heading Control 0 1 2 3 4 5 6 7 8 9 10
5. Airspeed Control 0 1 2 3 4 5 6 7 8 9 10
6. Sink-Rate Control $\phi < 33°$ 0 1 2 3 4 5 6 7 8 9 10
7. Sink-Rate Control $\phi > 33°$ 0 1 2 3 4 5 6 7 8 9 10
8. Total Task 0 1 2 3 4 5 6 7 8 9 10

Were there any malfunctions or distracting effects?

No: Yes:

SAFIR 1993

Fig. 12: Pilot Comment Card and Questionnaire

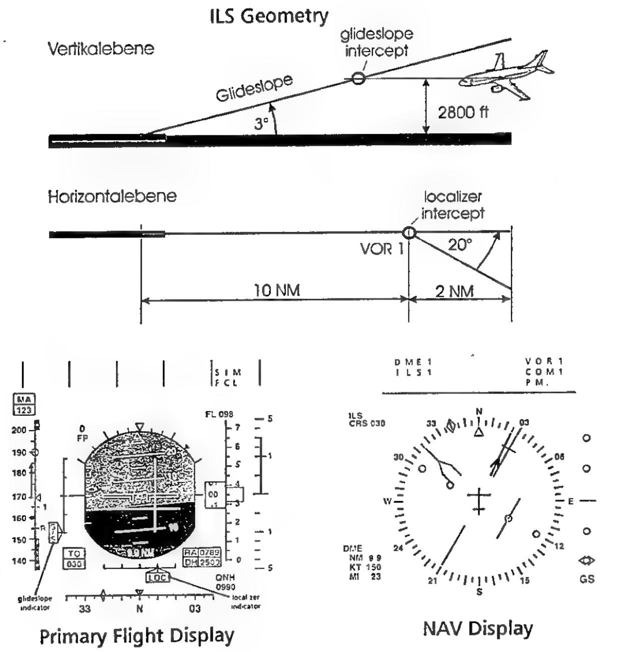
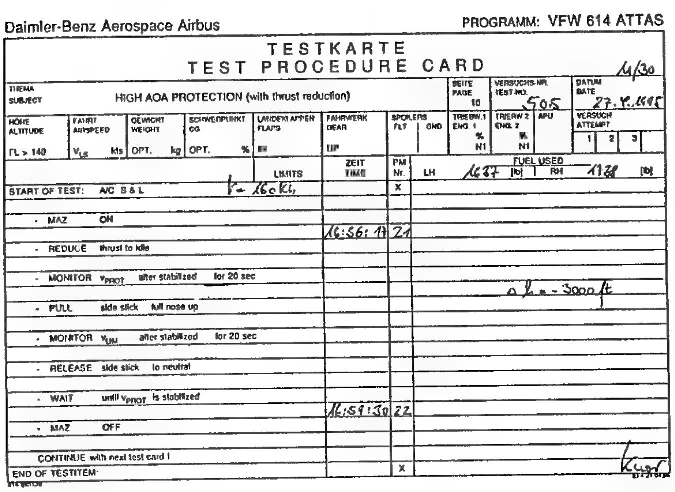


Fig. 13: Synthetic ILS Approach



Daimler-Benz Aerospace Airbus PROGRAMM: VFW 614 ATTAS

TESTKARTE
TEST PROCEDURE CARD 14/30

THEMA / SUBJECT: HIGH AOA PROTECTION (with thrust reduction) | SEITE / PAGE: 10 | VERSUCHS-NR. / TEST NO.: 505 | DATUM / DATE: 27.4.1995

HÖHE / ALTITUDE: FL > 140 | FAHRT / AIRSPEED: V_{LS} kts | GEWICHT / WEIGHT: OPT. kg | SCHWERPUNKT / CG: OPT. % | LANDEKLAPPEN / FLAPS | FAHRWERK / GEAR: UP | SPOILERS: FLT / GND | TRIEBW. 1 / ENG. 1: % N1 | TRIEBW. 2 / ENG. 2: % N1 | APU | VERSUCH / ATTEMPT: 1 2 3

	LIMITS	ZEIT / TIME	PM Nr.	FUEL USED LH 1637 [lb] RH 1738 [lb]
START OF TEST: A/C S & L	V = 160 kts		X	
- MAZ ON				
		16:56:17	21	
- REDUCE thrust to idle				
- MONITOR v_{PROT} after stabilized for 20 sec				
				$\Delta h = -3000$ ft
- PULL side stick full nose up				
- MONITOR v_{UM} after stabilized for 20 sec				
- RELEASE side stick to neutral				
- WAIT until v_{PROT} is stabilized				
		16:59:30	22	
- MAZ OFF				
CONTINUE with next test card !				
END OF TESTITEM			X	Kuo

Fig. 14: SAFIR Test Procedure Card

Flight - Experiment ***SAFIR 2***

ERR - Switch Declaration

Switch Nr.	Position	Effect	Function	coded by
00[1]	OFF ON	FALSE TRUE	ATTAS-flight test ATTAS fixed base simulator	DLR/DA
01[1]	OFF ON	FALSE TRUE	calibration signals off calibration signals on (∓ 80% max. Range)	DLR
02[1]	OFF ON	FALSE TRUE	alpha (normal) fuselage sensor and beta estimated alpha and beta from flight log	DLR
03[1]	OFF ON	FALSE TRUE	VTAS digital air data computer VTAS flight log	DLR
04[1]	OFF ON	FALSE TRUE	alpha floor off alpha floor engaged	DLR
05[1]	OFF ON	FALSE TRUE	ADA-Lane connected to IRS2 ADA-Lane connected to IRS1	DA
06[3]	OFF ON	FALSE TRUE	ILS not alive synthetic ILS approach (CRT-Mode 5: VOR/ILS)	DLR
07[3]	OFF ON	FALSE TRUE	normal law direct law	DA
codified combinations:				
08[2,3] 09[2,3]			deadspace: 0 1 2 3 0 1 0 1 0 0 1 1	DLR
10[2,3] 11[2,3] 12[2,3]			side stick characteristics 0 1 2 3 4 5 6 7 0 1 0 1 0 1 0 1 0 0 1 1 0 0 1 1 0 0 0 0 1 1 1 1	DLR
13[2,3] 14[2,3]			step/block inputs: no pitch 1 pitch 2 roll 0 1 0 1 0 0 1 1	DLR
15[3]	OFF ON	FALSE TRUE	test off: combinations of switches 8 to 14 can be set test on: switches 8 to 14 become effective	DLR/DA

ATTENTION: ✈ *auto-trim system must be switched off (TST04: on)*
✈ *CRT - Mode 5 must be switched on (for ILS-Approach)*

[1] Switch can be set during SIM OFF only
[2] Switch can be set during SIM ON only
[3] Switch must be set only if ERR15 = off
Code (switches 8 to 14) becomes valid for ERR15 = on

Hn / date 05.09.96

Fig. 15: SAFIR Switch Declaration List

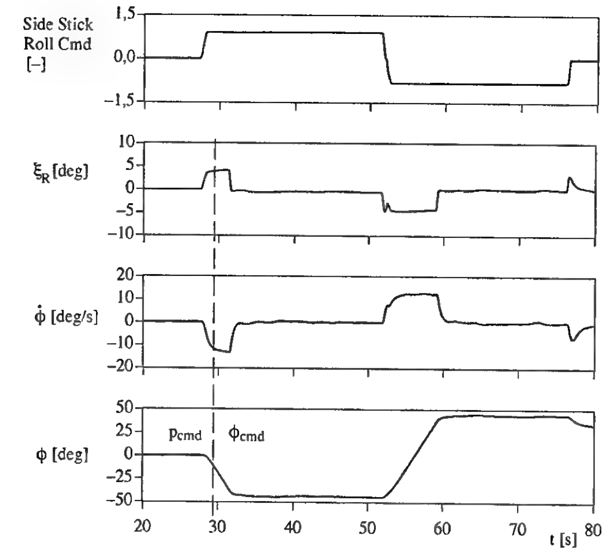


Fig. 16: Bank Angle Protection

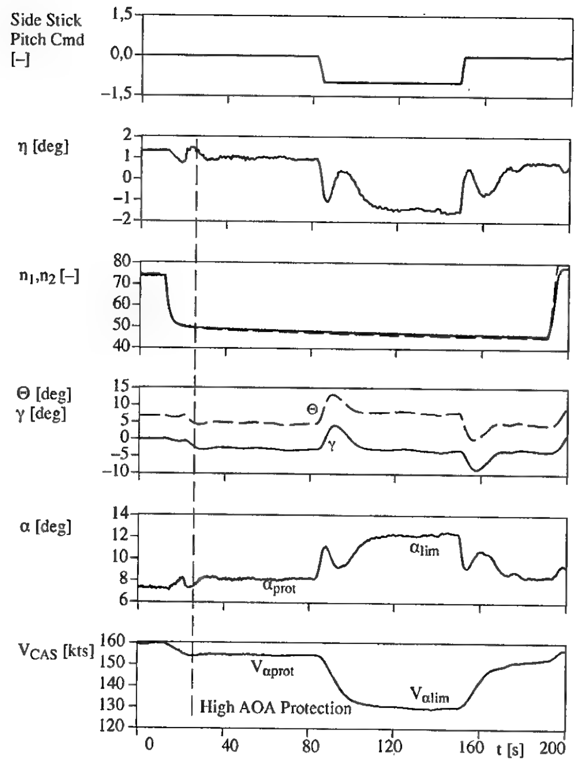


Fig. 17: High AOA Protection

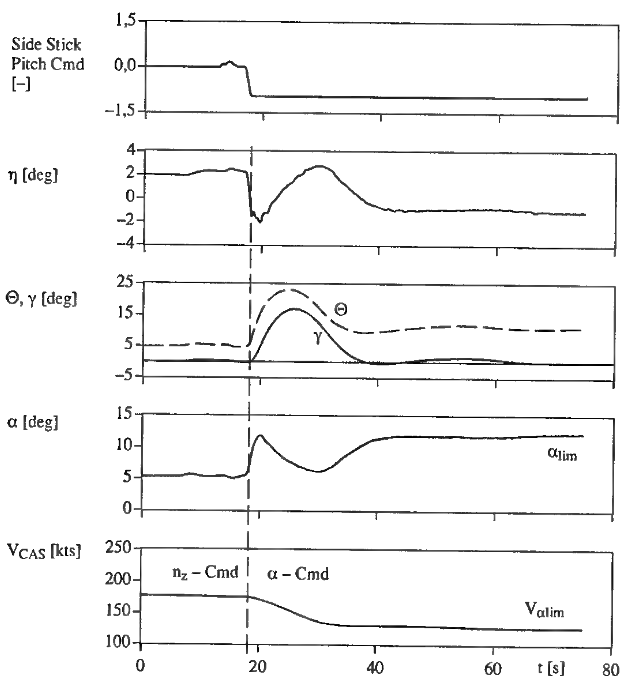


Fig. 18: High AOA Protection (dynamic)

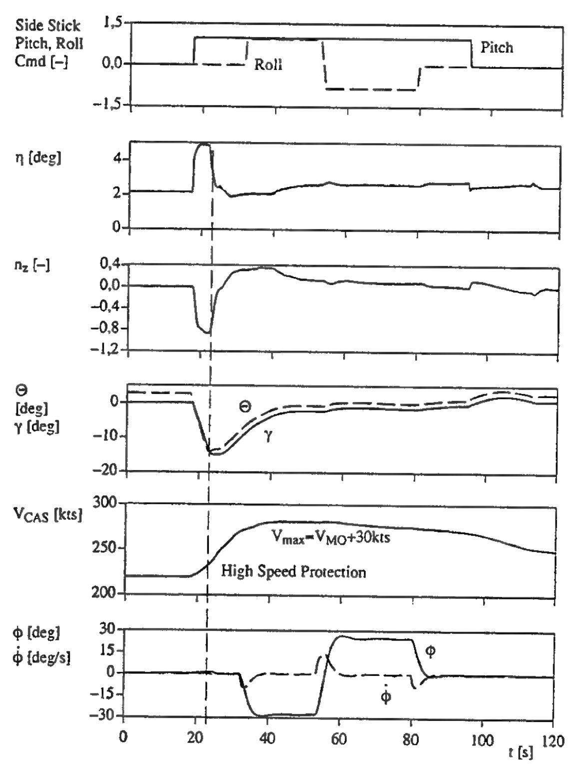


Fig. 19: High Speed Protection

Evaluation of High-Angle-of-Attack Handling Qualities for the X-31A Using Standard Evaluation Maneuvers

Patrick C. Stoliker and John T. Bosworth
NASA Dryden Flight Research Center
Edwards, CA 93523
U.S.A.

1. ABSTRACT
The X-31A aircraft gross-acquisition and fine-tracking handling qualities have been evaluated using standard evaluation maneuvers developed by Wright Laboratory, Wright-Patterson Air Force Base. The emphasis of the testing is in the angle-of-attack range between 30° and 70°. Longitudinal gross-acquisition handling qualities results show borderline Level 1/Level 2 performance. Lateral gross-acquisition testing results in Level 1/Level 2 ratings below 45° angle of attack, degrading into Level 3 as angle of attack increases. The fine-tracking performance in both longitudinal and lateral axes also receives Level 1 ratings near 30° angle of attack, with the ratings tending towards Level 3 at angles of attack greater than 50°. These ratings do not match the expectations from the extensive close-in combat testing where the X-31A aircraft demonstrated fair to good handling qualities maneuvering for high angles of attack. This paper presents the results of the high-angle-of-attack handling qualities flight testing of the X-31A aircraft. Discussion of the preparation for the maneuvers, the pilot ratings, and selected pilot comments are included. Evaluation of the results is made in conjunction with existing Neal-Smith, bandwidth, Smith-Geddes, and military specifications.

2. NOMENCLATURE

AOA	angle of attack, deg
CHR	Cooper-Harper rating
CIC	close-in combat
EFM	Enhanced Fighter Maneuverability
HARV	High Angle of Attack Research Vehicle
HUD	head-up display
KIAS	knots indicated air speed
LOES	lower-order equivalent systems
MATV	Multi Axis Thrust Vectoring
MAX AB	maximum afterburner
PIO	pilot-induced oscillation
PST	poststall
RPC	roll performance classification
SSLA	slow-speed line-abreast
STEM	standard evaluation maneuver

3. INTRODUCTION
Controlled flight at high angles of attack (AOAs) provides a modern fighter aircraft with the ability to turn rapidly, providing enhanced nose-pointing capability. The ability to accurately point the nose of the aircraft in a timely manner is the basis for handling qualities criteria and ratings. With the exception of recent flight programs such as the F-16 Multi Axis Thrust Vectoring (MATV),[1] F-18 High Angle of Attack Research Vehicle (HARV),[2] and X-29A,[3] an opportunity for flight test evaluations at poststall (PST) angles of attack has not existed. The Handling Qualities Military Standard (MIL-STD-1797)[4] provides a summary of criteria for handling qualities that have been derived primarily for a more conventional flight regime. Simulation-based criteria[5,6] have been developed to specifically address flight in the PST regime. Additional criteria[7–9] have also been developed to address handling qualities of modern augmented aircraft. Using the X-31A linear simulation, analytic evaluations of the handling qualities at high AOAs were performed to predict the characteristics of this aircraft.[10]

Designed specifically for investigation of flight in the PST regime, the X-31A Enhanced Fighter Maneuverability (EFM) program evaluated the benefits of thrust vectoring in a close-in combat (CIC) environment with emphasis on PST or flight at greater than 30° AOA. Following the completion of the original X-31A CIC objectives, a high-AOA handling qualities flight test program was performed. Standard evaluation maneuvers[11] (STEMs) were used to assess longitudinal and lateral gross acquisition and fine tracking at high AOAs. Pilot ratings and comments were collected immediately following each maneuver. These data were analyzed and compared with existing handling qualities criteria.

The development and preparation for the high-AOA handling qualities flight testing, a summary of the flight test data, a comparison of the results with existing handling qualities criteria, and a summary of lessons learned during the flight testing are covered in this paper.

4. AIRCRAFT DESCRIPTION
The X-31A airplane (fig. 1) is a single-seat fighter configuration with an empty weight of approximately 12,000 lbm that uses a single GE-F404-400 engine (General Electric, Lynn, Massachusetts). Fuel capacity is approximately 4000 lbm. Two aircraft were built by Rockwell International (Downey, California) and Daimler-Benz Aerospace (Germany). The wing planform is a double delta with an inboard leading-edge sweep of 56.6° and an outboard sweep of 45°. The wing area, span, and mean chord are 226.3 ft^2, 22.833 ft, and 12.35 ft respectively. Four trailing-edge flaps on the wing can be deflected symmetrically for pitch control and differentially for roll control. The leading-edge flap is scheduled to deflect as a function of AOA. The aircraft has an all-moving canard for pitch control and to meet the requirement for aerodynamic recovery from extreme AOAs. The vertical tail contains a rudder for directional control at AOAs less than 40°. Pitch and yaw moments can be generated by the three thrust-vector vanes. The inlet lip is moveable and is deflected as a function of AOA. These control effectors were all integrated into a control system[10,12] that provided the capability for good control throughout the AOA range.

In the longitudinal axis, the control system uses load factor command to a maximum 30° AOA. In the PST regime, from 30° to 70° AOA, deflections of the control stick command a

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

specific AOA. Three in. of aft stick commands 30° AOA; and full deflection, or 4.5 in., commands 70° AOA. This characteristic results in a stick sensitivity in AOA command of 33.3 deg/in of stick deflection. The nominal stick force is 5 lbf/in. The rate of change of AOA command was limited to 25 deg/sec. The longitudinal control system also includes an AOA command limiter that was set by the pilot. The AOA limiter provided the capability for the pilot to set the limit for the AOA command in 5° increments from 30° to 70° AOA.

For the lateral–directional axes, deflection of the control stick commands velocity-vector roll rate. The roll stick deflects 3 in. left and right. The maximum allowable roll rate is 240 deg/sec at a low AOA. In PST, the velocity-vector roll rate is between 30 and 50 deg/sec, scheduled as a function of dynamic pressure and AOA. During envelope expansion, the pilots had difficulty using full-lateral stick when using full-aft pitch stick because of interference with their legs. To accommodate this, the lateral-stick deflection–to–roll command gain was changed linearly from 1 to 2 between 30° and 70° AOA. This change results in full–roll rate command being generated with half-stick deflection at 70° AOA. The rudder pedals can be used to command sideslip at low AOAs, and their command authority is reduced to 0° at an AOA greater than 40°. The basic operation of the aircraft is designed for "feet-on-the-floor" flying.

The primary source of information for the pilot was the head-up display (HUD) (fig. 2). This display contained a conventional pitch ladder and heading display. Altitude and altitude rate were displayed on the upper right, while airspeed and Mach number were shown on the upper left. On the left side of the display were two tapes that showed the AOA and load factor. These data were displayed digitally at the top of the tapes. The current AOA command limit was indicated by an arrow next to the AOA tape. The HUD also contained a 2-mrad fixed pipper, depressed 2° from the waterline with an inner 20-mrad and outer 40-mrad reticle. Flight test instrumentation allowed in-flight recording of the HUD.

5. AIRCRAFT SIMULATIONS

Three simulations were used in the preparation for and analysis of the flight test maneuvers: a six-degrees-of-freedom, nonlinear simulation[13] that incorporated flight hardware and a fixed-base cockpit mock-up; a batch version of the six-degrees-of-freedom simulation; and linear simulations of the longitudinal and lateral–directional axes.

The cockpit for the piloted simulation incorporated the pilot displays and controls. A 5 ft by 6.5 ft flat screen projection provided the pilot a limited view out of the cockpit. The field of view for this screen was approximately 30 deg laterally and 20 deg vertically. One feature of the simulation was the capability to project a target aircraft that could be used for practicing the maneuvers. The target aircraft trajectory could be "flown" and recorded to allow for training with a repeatable maneuver.

The batch version of the simulation was used primarily for the generation of linear state-space models. Using these plant descriptions from the batch simulation, the linear simulation was used to generate transfer functions for use in the handling qualities criteria. These transfer functions could be used directly in the criteria evaluation or in the calculation of lower-order equivalent systems (LOES) parameters. The aerodynamic models for the linear simulation were fourth order. The control system included sensor models, filters, and high-order actuator models.

6. HANDLING QUALITIES EVALUATION

During the X-31A flight testing, an informal handling qualities evaluation was conducted during the CIC testing and formal evaluation using STEMs. The CIC testing was performed to evaluate the effectiveness of PST maneuverability.[14] From a predetermined set of starting conditions, the X-31A airplane was flown against an adversary aircraft. Both pilots were free to maneuver as required to try to establish a tracking situation. In addition to the test pilots assigned to the program, service pilots demonstrated the ability to become quickly familiar with the aircraft and to fly aggressively without any limitations on control stick inputs in the PST flight regime. In all of the CIC engagements, the pilots flew the aircraft aggressively to try to "win" the simulated combat.

CIC testing is used as a comparison with the formal handling qualities testing because of the demonstrated ability of the X-31A pilots to successfully accomplish gross acquisitions and perform fine tracking in a high-gain environment at high AOAs. During CIC evaluation, the X-31A aircraft was generally able to outperform adversary aircraft by using PST maneuvers. Although no handling qualities ratings were made during these tasks, the general consensus was that the X-31A aircraft had good handling qualities (Level 1 or Level 2) in this flight regime, and no major handling qualities deficiencies were noted. Similar handling qualities were expected from the STEM evaluations. A disadvantage of using CIC to evaluate handling qualities is that the AOA varies considerably and the handling qualities characteristics cannot be sorted out as a function of AOA.

A method for providing consistent techniques for flight-test handling quality evaluation has been addressed by the definition of a set of STEMs.[11] These maneuvers can obtain evaluations at a constant AOA that can then be compared to analysis. During a limited flight test evaluation, the X-31A aircraft used four evaluation maneuvers: three STEMs, and a maneuver developed from CIC testing. The flight test maneuvers were derived from STEM 10 (High-AOA Longitudinal Gross Acquisition), STEM 3 (High-AOA Lateral Gross Acquisition) and STEM 2 (High-AOA Tracking). The chase airplane for the X-31A aircraft, an F-18 aircraft, was used as the target airplane. Data were collected using a pilot rating sheet that was completed immediately following each maneuver, postflight interviews, a review of in-flight video recordings made through the HUD, and a comprehensive set of telemetered data. The techniques for performing these maneuvers were developed using experience gained from the F-18 HARV program. In order to emulate the acquisition and tracking tasks that were performed during the CIC investigation using the X-31A airplane, an additional evaluation maneuver was flown. This maneuver used slow-speed line-abreast (SSLA) initial conditions and resulted in acquisition and tracking tasks at a variety of AOAs. The formal handling qualities testing covered a 5-month period and used five different pilots during the performance of 19 flights.

Flight preparation involved practice in the simulator to establish guidelines for maneuvering the test and target aircraft. The initial starting positions, target maneuver, and timing were defined so that the gross-acquisition or fine-tracking tasks occurred at a specific AOA. To accurately achieve consistent

initial starting conditions, two operational ground radars were required because the X-31A aircraft was not equipped with a radar. During testing, the pilots could achieve consistent spacing without the ground radars by comparing the relative target size with the HUD reticle.

Pilot comments were recorded on a questionnaire immediately following each maneuver. The completion of the questionnaire required a pilot rating using the Cooper-Harper rating (CHR) system[15] (fig. 3) and an evaluation of the confidence class (fig. 4). The confidence class rating was used to help assess the effectiveness of the maneuvers for rating handling qualities. Changing the initial conditions or additional practices improved the confidence class ratings. Pilot comments were solicited regarding difficulty, predictability, aggressiveness effects, and control system effects. Following these comments, a pilot-induced oscillation (PIO) rating (fig. 5) and a second CHR were recorded. For lateral gross acquisitions, a rating using the roll performance classification (RPC)[16] (fig. 6) was also solicited. The RPC was developed through simulation studies to address the open-loop nature of lateral gross acquisition. The RPC is intended to judge the initial rate and rate onset and is not based on the ability to arrest the roll rate. The pilot comments were transcribed using the HUD video recordings that were available for every flight.

Each maneuver was also evaluated using the telemetered data. Linear models were calculated for each maneuver based on the AOA, airspeed, altitude, and estimated fuel state. The linear models were used to generate the parameters and frequency responses required for the handling qualities criteria.

6.1 Longitudinal Gross Acquisition

STEM 10 was used as the basis for the longitudinal gross-acquisition task. The X-31A airplane started 3000 ft in trail of the target aircraft. At the initiation of this maneuver, the target aircraft entered a steady turn to the conditions indicated in Table 1. After predetermined time delays, the X-31A pilot selected maximum afterburner (MAX AB), rolled the aircraft so that the target aircraft was in the pitch plane, and then aggressively pulled to capture the target in the pitch plane within the criteria (fig. 7). The pipper and reticles in the HUD provided a reference for evaluating the gross-acquisition and fine-tracking tasks. The goal of the tasks was not to drive the pipper to the target, but to acquire or track the target within the specified criteria in relation to the pipper. The timings were selected so that the gross acquisition would occur at the desired AOA of either 30°, 45°, or 60°. The AOA limiter was not used during this testing. Table 1 shows the maneuver timing for each flight condition.

6.2 Lateral Gross Acquisition

Lateral gross acquisitions were flown using STEM 3 as a baseline. For these maneuvers, the target aircraft established a steady turn at specified conditions, and the pilot of the X-31A aircraft maneuvered the aircraft to the target AOA (30°, 45°, or 60°) at maximum afterburner. Depending on how rapidly the pilot applied aft stick, the aircraft could be at 1 *g* or an elevated load factor at the desired AOA. When the target aircraft was at a prespecified angle away from the nose of the X-31A aircraft, the X-31A aircraft was maneuvered aggressively using only lateral stick to acquire the target in the roll plane within the criteria (fig. 8). Table 2 shows the initial conditions for these maneuvers. To assist the pilot in remaining at the targeted AOA and to try to constrain the maneuver to the lateral axis, the AOA command limiter was set to the desired value.

Table 1. Task descriptions for longitudinal gross acquisition.

Flight condition	Maneuver timing	Maneuver description
30° AOA, Mach 0.45	T = 0	Target begin maneuver: MAX AB, constant 20° AOA turn, maintain 200 KIAS.
	T + 4 sec	X-31A advance throttle to MAX AB.
	T + 4 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.
30°AOA, Mach 0.60	T = 0	Target begin maneuver: MAX AB, constant 20° AOA turn, maintain 200 KIAS.
	T + 4 sec	X-31A advance throttle to MAX AB.
	T + 5 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.
45°AOA, Mach 0.50	T = 0	Target begin maneuver: MAX AB, constant 25° AOA turn, maintain 170-180 KIAS.
	T + 5 sec	X-31A advance throttle to MAX AB
	T + 7 sec	X-31A roll in plane with target, perform rapid pull to 45° AOA.
60°AOA, Mach 0.50	T = 0	Target begin maneuver: MAX AB, constant 25° AOA turn, maintain 170-180 KIAS.
	T + 5 sec	X-31A advance throttle to MAX AB.
	T + 8 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.

Table 2. Task descriptions for lateral gross acquisition.

Angle of Attack	Test Condition	Test Description
30°	170 KIAS X-31A 1500 ft Echelon and behind F-18	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/ attitude to maintain conditions.
	AOA limit = 30°	X-31A: MAX AB, pull to 30° AOA. When target is 30° off nose, acquire target laterally.
45°	170 KIAS X-31A 1500 ft Echelon and behind F-18	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/ attitude to maintain conditions.
	AOA limit = 45°	X-31A: MAX AB, pull to 45° AOA. When target is 30°-45° off nose, acquire target laterally.
60°	170 KIAS X-31A 1500 ft Echelon and behind F-18	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/ attitude to maintain conditions.
	AOA limit = 60°	X-31A: MAX AB, pull to 60° AOA. When target is 30°–45° off nose, acquire target laterally.

6.3 Fine-Tracking Evaluation

The fine-tracking evaluation consisted of two phases. Phase 1 testing was performed at AOAs of 10°, 15,° and 20° to establish a reference point for comparison with other conventional AOA evaluations and testing in the PST regime. During phase 1, fine tracking was performed only in the longitudinal axis. Phase 2 testing, based on STEM 2, evaluated fine tracking at AOAs of 30°, 45,° and 60° for the longitudinal and lateral axes. The AOA command limiter was not used in fine-tracking evaluations.

Initial testing in Phase 2 concentrated on longitudinal fine-tracking evaluations while the maneuver setup was refined. Because only one axis was being evaluated at a time, the maneuver had to be set up with the target approximately in the reticle so that maneuvering could be performed only in the axis being evaluated. After an acceptable set of starting conditions was developed, the same setup was used for the longitudinal and lateral tracking tests at each AOA. The X-31A pilot would practice the maneuver to ensure that the setup would result in the desired AOA and then perform the maneuver twice. First, a longitudinal fine-tracking task was performed and pilot ratings were given. Then a second maneuver was performed where lateral tracking and ratings would be done. Table 3 shows the maneuver sequence and figure 9 shows the criteria. To test the ability to make precise longitudinal changes in track point, the maneuver description called for the pilot to move the pipper from nose to tail. Similarly, the lateral tracking task required the movement of the pipper from wing tip to wing tip.

6.4 Combined Maneuvers

Pilots consistently commented on the difference between the types of maneuvers used in the handling qualities evaluations and the maneuvering performed during CIC. To address the perceived handling qualities differences between CIC and STEMs, a combined maneuver was evaluated during one flight. For this maneuver, the starting conditions were those of the SSLA setup from the CIC flight tests. The X-31A and F-18 aircraft started side by side at the same speed and altitude—215 knots indicated airspeed (KIAS) and 25,000 ft—separated by 1500 ft. For the handling qualities evaluation, the maneuvering began on the call of the X-31A pilot. The aircraft initially turned towards each other with the X-31A aircraft going over the target aircraft. Then the F-18 aircraft performed a single heading reversal and maintained a steady turn at 30° AOA and 170 KIAS. The X-31A aircraft maneuvered as required to acquire and track the target. Multiple acquisitions were achieved by lagging off of the target aircraft and then maneuvering aggressively to reacquire the target. Figure 10 shows the rating criteria.

7. HANDLING QUALITIES RESULTS

Handling qualities testing was done during 19 flights over a 5-month period in 1994. Five pilots participated in the testing, using both X-31A aircraft. When acquiring the pilot comments at the completion of each maneuver, a CHR was solicited before and after the detailed comments. Having the pilot repeat the CHR at the end of the questionnaire allowed a reassessment of the rating in light of the more detailed comments and

Table 3: Task descriptions for fine tracking.

Angle of Attack	Test Condition	Test Description
10°	0.80 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 3 g, adjust power/attitude to maintain conditions.
		X-31A: Roll and pull to 10° AOA for longitudinal tracking.
		(Repeat with target at 1.8 g and initial Mach number of 0.60.)
15°	0.75 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 3.5 g, adjust power/attitude to maintain conditions.
		X-31A: Roll and pull to 15° AOA for longitudinal tracking.
		(Repeat with target at 2.1 g and initial Mach number of 0.55.)
15°	0.70 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 4.0 g, adjust power/attitude to maintain conditions.
		X-31A: Roll and pull to 20° AOA for longitudinal tracking.
		(Repeat with target at 2.4 g and initial Mach number of 0.50.)
30°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 180 KIAS/ 25° AOA, adjust power/attitude to maintain conditions.
		X-31A: MAX AB, at 20° angle off, roll and pull to 30° AOA for tracking.
45°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 160 KIAS/ 30° AOA, adjust power/attitude to maintain conditions.
		X-31A: MAX AB, at 30° angle off, roll and pull to 45° AOA for tracking.
60°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/attitude to maintain conditions.
		X-31A: MAX AB, at 45° angle off, roll and pull to 60° AOA for tracking.

discussion. The second rating given is used as the reference for this report. The first and second CHR were generally the same.

7.1 Longitudinal Gross Acquisition

Longitudinal gross-acquisition tasks were flown on five flights by three pilots. The initial timings for these maneuvers were based on the piloted simulation. Because of the limited field of view provided by the projection television display in the simulator, transferring this simulation experience to flight was difficult. A total of 49 gross-acquisition tasks were performed with 28 receiving pilot ratings. Twenty tasks were practices and one task was an unsuccessful gross acquisition. Eleven of the practice maneuvers occurred on the first flight. Results from this first flight were used to refine the maneuver timing, and consequently, each of the other pilots typically required only one practice at each target AOA. The goal was to collect data at 30°, 45°, and 60°, with the actual AOA for acquisition falling between 22° and 65°.

It became apparent after testing started that horizontal bands located in relationship to the pipper as specified by the performance criteria (25 or 40 mrads) rather than a circular reticle would have provided the pilot with the appropriate reference for the task. Review of the HUD data and telemetry data showed that, during acquisition, if the target was entering the HUD field of view on either side of the reticle, a lateral input to bring the target within the reticle often occurred.

Figure 11 shows the CHRs plotted as a function of AOA. These data show a trend for CHRs increasing from "2" to "4" as AOA increased from 20° to 65°. The one CHR of "5" was the result of a very large overshoot during capture. For these maneuvers, the pilots developed a technique to put in a nearly full–aft stick initial input and then leading the AOA capture with forward stick. As a compensation technique, Pilot B noted, "I'm starting to get a feeling for when I need to lead the pitch rate to get the capture task." Figure 12 shows this phenomenon where maximum pitch rate during the maneuver is plotted as a function of AOA. At the higher AOAs, the pilots would hold aft stick longer, allowing a larger buildup of pitch rate prior to the countering control movement.

A confidence class rating of "A" was given for all but one of the maneuvers, meaning that the pilots' ratings were assigned with a high degree of confidence. The PIO ratings for 18 of the 28 tasks were "1," indicating that the pilots observed no undesirable motions. The remaining tasks received a PIO rating of "2," indicating undesirable motions that did not compromise task performance. These data indicate that the X-31A aircraft would have Level 1 performance at less than 40° AOA. The trend would be for borderline Level 1/Level 2 at AOAs greater than 40°. These ratings matched the expectations from the CIC testing.

In conjunction with these pilot ratings, a number of pilot comments add insight into the data. During the testing where the target AOA was 30°, Pilot A reported, "Thirty is the critical point. It's better [for the evaluation] to be above 30; below 30 is too easy." For the PST AOAs, the pilots consistently noted that the stick forces were too heavy and that the stick motion was too large. For the acquisitions at 45° and 60°, the pilots noted a lateral disturbance that complicated the task. This disturbance was noted during envelope expansion and was attributed to asymmetric forebody vortex cores that changed as a function of AOA.

Figure 13 shows an example time history for gross acquisition at 45° AOA. To show pitch-stick movement, a comparison of AOA command with AOA response and pitch-rate response are shown. Nearly full-aft stick is used to initiate the maneuver, followed by a number of stick inputs on the order of one-half inch. These small stick displacements result in a rate-limited AOA command. An inspection of the trailing-edge flaps and thrust-vector vanes also showed periods of rate limiting. None of the pilot comments indicated that rate limiting in either the command path or in the control surface response affected the handling qualities.

7.2 Lateral Gross Acquisition

The lateral gross-acquisition task was performed by four pilots during five flights. Nineteen of the total 49 acquisitions received pilot ratings (fig. 14). The remaining 30 maneuvers were practices. Two of the pilot ratings are not included in the summary of data because the AOA varied from 60° to 35° during attempted gross acquisitions at 60° AOA. The large number of practices required for this task shows the increased difficulty over the longitudinal gross acquisitions. Unlike the longitudinal acquisitions, where the task was primarily confined to one axis after the X-31A aircraft was banked into the correct plane, the lateral acquisitions required motion in multiple axes. First, the aircraft is performing velocity-vector rolls that result in a significant coning motion at high AOA. This motion is further complicated by the fact that the velocity vector settles during the maneuver. During extended maneuvers, the velocity vector is almost straight down, allowing the "helicopter gun attack." It should be noted that Pilot E had two sorties on one day and required the same level of practice maneuvering in both flights. This pilot had also practiced similar maneuvers in a domed simulation, which increased familiarity with the task being performed.

During the initial flight practices, the acquisition was not occurring at the desired AOA with the target in the HUD field of view. Adjustments were made in the distance the X-31A aircraft was trailing the target aircraft, the lateral displacement from the target aircraft, and the offset angle after the target began maneuvering before the X-31A pilot initiated acquisition. Typical difficulties with the performance of these maneuvers were loss of sight of the target aircraft by the pilot under the nose of the X-31A aircraft, causing termination of the maneuver for safety concerns, and acquisition of the target above or below the HUD field of view as a result of improper initial lateral offset.

Figure 14 shows a comparison of CHRs with AOA, revealing a degradation in handling qualities as AOA is increased. The cases near 30° AOA generally fall into the Level 1 category. At 45°, the pilot ratings are consistent with Level 2 handling qualities. At 60 °, the trend is for Level 3 handling qualities. For this task, the majority of the maneuvers (11 of 17) were given a confidence class rating of "B," which shows only a moderate degree of confidence in the ratings. All of the data at AOAs greater than 50° were rated confidence class "B." Based on pilot comments, this rating can be attributed to the difficulties with adjusting the initial conditions to account for the multiple-axis maneuvers required of the X-31A aircraft. The general trend for increased CHRs with increasing AOA is present in the ratings regardless of the confidence class rating.

This task did not emulate the lateral acquisitions performed during CIC testing. During simulated combat, the X-31A

aircraft typically maneuvered within the turn radius of the target aircraft. The X-31A velocity vector was nearly straight down, resulting in a "helicopter gun attack." The CIC results did not indicate a tendency for Level 3 handling qualities at the higher AOAs. While this task did identify handling qualities deficiencies, it is not clear that the STEM task is representative of the maneuvering pilots may be required to perform in the PST flight regime. For the STEM, the pilot had to aggressively initiate the maneuver with full-lateral stick; while in CIC testing, the pilot input was proportional to the change in nose-pointing angle required.

The PIO ratings tended to increase as a function of AOA. Three cases had a rating of "2"; undesirable motions were present but did not affect task performance. An additional three cases had a rating of "3," indicating that undesirable motions did compromise task performance. One case was given a rating of "2–3," also falling into the category of undesirable motions. Two cases showed nondivergent oscillations and received a PIO rating of "4." Two cases did not receive a PIO rating, and six cases had a rating of "1."

Figure 15 shows stability-axis roll rate for each maneuver plotted as a function of AOA and shows that, for the PST range, that rate was relatively constant at approximately 40 deg/sec. The peak rate occurred for a maneuver at 25° AOA, and in general, the higher roll rates were the result of the pilot using roll stick before achieving the desired AOA while the aircraft was still pitching up. Nine maneuvers received an RPC rating of "2," or satisfactory. Eight cases received ratings of "2.5," which falls between the satisfactory and unsatisfactory levels. One maneuver received a RPC rating of "1," which equates to enhancing or tactically superior. This maneuver had the second highest stability-axis roll rate. The pilot commented, "I would say it's just fine tactically. I got around as fast as I wanted to." Although the onset rate was good, the pilot was unable to accurately arrest the roll rate, resulting in a CHR of "8" and a PIO rating of "4." Addressing the undesirable motions, the pilot stated, "Lots of them. Many overshoots; borderline PIO at the end." The pilot also noted that the task was "very difficult."

Figure 16 shows time histories. It can be seen that the pilot used full-stick displacement three times during the maneuver with a peak stability axis roll-rate command of 40 deg/sec. Although the stability-axis roll rate was high for this flight condition, the pilot had difficulty using it effectively for the aggressive gross-acquisition task. These data indicate that using the RPC to assess only the roll onset does not necessarily equate to good gross-acquisition performance.

During the performance of this task, the pilots regularly used full–roll stick displacement, regardless of the AOA. For the high AOAs, this displacement would be more than required to get maximum roll command because of the modification in the relationship between stick deflection and full–roll rate command discussed above. One reason for this excess displacement would be that no feedback to the pilot exists when full-roll command is generated. No pilot comments were directed towards any effects caused by the limiter that result when the pilot stick deflection is larger than actually required for full-roll command. Examination of the time histories do not indicate any particular effects from the control inputs. Analogous to the longitudinal task, rather than a circular reticle, vertical bands at the specified distance from the pipper would have provided the pilot with a more appropriate reference for the task.

7.3 Fine-Tracking Evaluation

Fine tracking was evaluated during eight flights by three pilots. In Phase 1 testing at low AOAs, 17 tracking tasks were performed and 9 maneuvers rated. Of the eight practices, six were required in the first flight. During Phase 2 testing at high AOAs, 45 tracking tasks were performed. A total of 19 practices were required, and 16 longitudinal and 10 lateral fine-tracking tasks were rated. During the first flight, six practices were required to get initial conditions that allowed one scorable task. For the next 3 flights, efficiency improved, with 9 practices required to get 13 maneuvers that could be rated. As the target AOA increased, two or three practices were required to achieve the desired aircraft positioning at the target AOA. The last 2 flights required only 1 practice for 13 scorable maneuvers.

One factor that affected the pilot ratings was the amount of time spent tracking. The original flight cards called for 4 sec of tracking. However, the pilots often spent 20 sec or more performing the tracking task, resulting in significant variations in flight condition (particularly AOA). In one case where the intended AOA was 30° but the tracking occurred between 30° and 23°, the pilot commented, "There were two distinctive airplanes. When I was at the initial AOA around 30°, it was quite a bit harder to track than when I settled in. My rating will be associated with the initial values of the tracking." Not all of the pilots were as concise in identifying the AOA range for their rating, and the engineers had to identify the AOA.

7.3.1 *Longitudinal Fine Tracking*

Initial difficulties with fine tracking resulted from the initial conditions of the aircraft. The spacing of 3000 ft used during the longitudinal gross acquisitions was reduced to 1500 ft, but the maneuver timing used for gross acquisition was not changed. This change resulted in the X-31A aircraft going a considerable distance downrange while the target was maneuvering. When the X-31A airplane was maneuvered, it was outside the turn of the F-18 airplane. Suggestions from the pilot in the control room to base the maneuver on the relative angle between the aircraft allowed the one scorable maneuver in the first flight. During the subsequent flights, the start time for the X-31A maneuver was based on the off-boresight angle and resulted in more repeatable tasks.

Figure 17 shows CHRs plotted as a function of AOA and shows an increase in rating (or decrease in handling qualities) as AOAs increases. For AOA less than 30°, the ratings are consistently "3" or less, indicating Level 1 handling qualities. Between 30° and 50° AOA, the ratings ranged between "3" and "7." The highest ratings are at the highest AOAs. This range would be rated Level 2 with two Level 3 ratings near 50° AOA.

All of the ratings were in confidence class "A" for AOAs less than 30°. For the PST ratings, ten were in confidence class "A" and six were rated "B." These ratings reflect a high degree of confidence for most of the ratings. All the pilots noted that the tracking task used for the handling qualities evaluation was different from the type of tracking that was done during the CIC evaluations. One pilot summarized it by saying, "The tracking we're trying to do here is kind of dynamic-pitch tracking and not the kind of tracking we typically did during the end game, which tended to be more in matching yaw rates." PIO ratings also tended to increase with AOA for this task. The ratings ranged between "2" and "4," indicating undesirable motions and oscillations throughout the PST range.

The initial instructions for the fine-tracking tasks called for nose-to-tail tracking. Because of the unique geometries that could result during the high-AOA maneuvering, the tracking tasks required both lateral and longitudinal stick inputs to perform the nose-to-tail tracking because the maneuver plane of the X-31A airplane would not correspond with the plane of symmetry of the target aircraft. This instruction was modified to state that tracking was not necessarily from nose to tail, but should use only pitch stick inputs and use the appropriate aircraft features as a reference. Even with the modified instructions, the pilots would often use diagonal stick inputs during the tracking tasks.

7.3.2 *Longitudinal Fine-Tracking Handling Qualities Criteria*

The X-31A data were evaluated using the Neal-Smith, bandwidth, and Smith-Geddes criteria to assess the applicability at high AOAs. These criteria are all based on the pitch stick–to–pitch attitude transfer function. An analytic study[10] had shown that other criteria based on LOES were not applicable to high-AOA flight. Transfer functions were generated using the linear models based on the mass properties and flight conditions (Mach number, altitude, and AOA) associated with the pilot ratings. The transfer functions were used in the criterion assessment and correlated with the pilot ratings. With the exception of a few data points, the linear analysis results correlate with handling qualities ratings obtained in flight. The low-AOA data and the data with CHRs of "3" tend to fall into the Level 1 regions for all of the criteria. The data with the higher CHRs seem to fall in clusters, and for all the criteria, these clusters move away from the Level 1 regions.

Figure 18 shows X-31A data plotted using the Neal-Smith criterion.[7] The Neal-Smith criterion uses a simple compensator model to close the loop of the pitch stick–to–pitch attitude transfer function. The magnitude of the resonant peak in the resulting closed-loop transfer function is compared with the phase angle of the compensation. The high-AOA data indicate that less lead compensation can be allowed. With two exceptions, data with Level 1 ratings required less than 15° of lead compensation. A cluster of data near 40° of lead compensation with adjacent CHRs of "5" and "7" exists that may indicate the proximity of the Level 3 boundary. Figure 14 shows the existing boundaries as solid lines, and boundaries indicated by the X-31A PST data are shown as dashed lines. Additional data are required to determine if these boundaries are valid.

For the bandwidth criterion[9] (fig. 19), all of the data show an estimated equivalent time delay of approximately 0.04 sec. This criterion has correlated handling qualities with the estimated equivalent time delay and bandwidth frequency calculated from the pitch stick–to–pitch attitude transfer function. A reduction in bandwidth exists that is consistent with an increase in AOA and CHR. The X-31A data indicate that the Level 1 boundaries are reasonable. Several data points exist with a bandwidth of approximately 3 rad/sec that have CHRs of "5" and "7," indicating that it might be appropriate to move the Level 3 boundary to this bandwidth as shown by the dashed line.

When compared with the Smith-Geddes criterion[8] (fig. 20), the X-31A data indicate that the slopes of average CHR as a function of phase angle at the bandwidth frequency need to be steepened. The criterion calculates the bandwidth frequency based on the slope of the gain relationship from the pitch attitude–to–pitch stick transfer function. In general, the tolerance bands for the average CHR would be valid for most of the data points with a pilot CHR of "3" or "4." An alternate relationship between average CHR and phase angle at the bandwidth frequency is presented as a dashed line.

The one data point that is anomalous for all three criteria is the 30° AOA tracking case that received a CHR of "6." The confidence class rating was "A," indicating a high degree of confidence in the rating. In addition, the PIO rating of "3" indicated that undesirable motions affected the pilot's ability to perform the task. The pilot did attribute some of the difficulty to aggressiveness, commenting, "The more aggressive you are, the more you oscillate." Another pilot performing a similar maneuver gave a better CHR of "4," but also commented, "If you are aggressive, you get undesired motions." Other than pilot technique, one difference noted between the two tasks was that the task that received the degraded rating was performed at a higher airspeed. An analytic investigation of handling qualities[10] did show a degradation in predicted handling qualities during PST flight as airspeed increased with a constant AOA.

7.3.3 *Lateral Fine-Tracking*

Figure 21 shows CHRs plotted as a function of AOA. As with the longitudinal tracking data, some scatter in the ratings exists near 30° AOA, but the trend is toward higher CHRs as AOA increases. The three data points at an AOA at or greater than 40° had confidence class ratings of "B." The lower AOA data received a confidence class rating of "A." The PIO ratings are consistent with the other tasks in that an increase in undesirable motions as AOA increased existed, with oscillations being reported at the highest AOAs.

A consistent pilot comment was, "The more aggressive you are, the harder the time you have tracking." As well as the impact of aggressiveness on the task performance, the pilots also commented that the task frequently required diagonal stick inputs as opposed to pure lateral stick motions. Lateral tracking initially required wing tip–to–wing tip tracking. The tracking task was redefined to use only lateral stick inputs, but the pilots continued to use diagonal inputs.

7.3.4 *Lateral Fine-Tracking Handling Qualities Criteria*

Using LOES derived from the linear models, dutch roll frequency, dutch roll damping, the roll-mode time constant, and the equivalent time delay were calculated and compared with the criteria from MIL-STD-1797 (fig. 22 and 23). These criteria predict Level 1 handling qualities throughout the AOA range, which is not consistent with the handling qualities ratings. These data indicate that dutch roll frequency and damping and the roll-mode time constant are not the factors affecting high-AOA handling qualities.

The lateral fine-tracking ratings were also compared with the Smith-Geddes criterion[8] (fig. 24). Although a limited amount of data exists, there appears to be general agreement with this criterion.

Some caution must be used when applying the results of linear analysis to the lateral–directional high-AOA tracking tasks. Several nonlinear effects are evident in the data. The flight condition changes rapidly during the task from a high-speed, high-AOA condition to a low-speed, reduced-AOA condition. The maximum roll-rate command is scheduled as a function of airspeed so that the pilot experiences a reduced command authority as the airspeed decreases. The rate limit for the stability-axis roll-rate command was reached several times

during the fine-tracking tasks. The high workload demand on the thrust-vectoring system resulted in rate limiting of the thrust-vector paddles. Also, at high AOAs, moving the pipper from wing tip to wing tip required a combined lateral and longitudinal stick input.

Even a full six-degrees-of-freedom nonlinear simulation did not entirely reproduce the dynamics observed during some of the lateral fine-tracking tasks. Figure 25 shows some of the excursions in yaw rate and sideslip angle that were not duplicated with the nonlinear simulation. These excursions approximately correlate with target overshoots where the target wanders outside the 20-mrad reticle and may be related to asymmetric forebody vortex cores. To accurately predict handling qualities requires an analytic model that includes all of the dynamics, so the effect of these vortices should be included.

7.4 Combined Maneuvers

The combined maneuver was flown four times during one flight by one pilot. Two of the maneuvers were used for practice. Comments and CHR ratings of "3" and "4" were given on the other two maneuvers. No distinction existed in the ratings for lateral or longitudinal tasks, but fine tracking and gross acquisition were rated separately. In summary, the ratings were given with high confidence and were borderline Level 1/ Level 2 for both tracking and acquisition. No undesirable motions were present during the gross acquisition, and the motions did not affect the task during fine tracking. Following the flight, the pilot reported, "The SSLA setup was an excellent starting condition to evaluate handling qualities in the PST regime."

Figure 26 shows time history data from the second rated maneuver, which spanned 60 sec. The AOA ranged between 30° and 70°. Pitch-stick sensitivity can be seen in the AOA command where 15° excursions in the command at the AOA command rate limit of 25 deg/sec can be seen. Full-roll stick was used early in the maneuver, and approximately 66 percent of the stick deflection was used in a later acquisition. Peak velocity-vector roll rates of nearly 40 deg/sec were observed. The fourth trace shows the timing for the three gross acquisitions performed and the periods of tracking. This maneuver was initiated at an altitude of 25,000 ft and was completed at an altitude of 14,000 ft.

As with the other tasks, the pilot commented that the stick forces were "too heavy" and the motions were "too large." Because this maneuver intentionally used diagonal stick inputs, the pilot was able to comment on stick harmony, "The stick movement is much too high; and you have the nonharmony between the pitch stick, which is so sensitive, and the roll stick, which is not so sensitive."

Because the pilot ratings cover maneuvers that span a large flight envelope and encompass two axes of control, comparing them with analytic results is difficult. The pilot liked this maneuver better and felt it was more representative of the type of flying done during the CIC investigation. The maneuver also resulted in the Level 1/Level 2 ratings that were expected. Additional testing is required, but this type of maneuver may provide a better means of evaluating the PST handling qualities, but like CIC, it is of limited value for analysis or design because of the varying flight conditions.

8. LESSONS LEARNED FOR HIGH-ANGLE-OF-ATTACK HANDLING QUALITIES TESTING

When flying a new task, backup cards should be prepared for an established task in the event the first task is not working out. During the first PST fine-tracking flight, it was quickly apparent to the pilots in the airplane and on the ground that the test as designed would not result in an acceptable fine-tracking task. Almost an entire flight was used to get one data point. Testing of alternate flight cards would have collected additional data, and ground review would have adjusted the test setup for the acquisition of PST fine-tracking data.

Some of the pilots thought a domed simulation would have helped them better prepare for the tasks. But it is interesting to note that during the lateral gross acquisitions, the one pilot who had performed the maneuvers in a domed simulation required the same amount of in-flight practice as the other pilots.

Care should be taken in task definition. For the fine-tracking tasks, the pilots were asked to do separate longitudinal and lateral tracking tasks. Even with instructions that the inputs should be limited to pitch or roll inputs, the pilots continued to use diagonal stick motions to perform the more classical tracking tasks of nose-to-tail and wing tip–to–wing tip. The task definition should also include a reasonable time limit for the performance of the task. One of the reasons 4 sec was initially chosen was to try to minimize variation in flight condition during the performance of the task. This time limit was not enforced during the testing and resulted in a tracking task that lasted 20–30 sec with large AOA variations.

Modifications to the HUD could have provided the pilots with the proper cues for the tasks. For longitudinal gross acquisition, horizontal bars at 25 and 40 mrads would have provided the proper reference for the task that was being rated. Similarly, vertical bars could have been used for lateral gross acquisition in place of the circular reticles. This display might reduce the tendency of the pilot to try to place the pipper on the target.

9. CONCLUSIONS

The Standard Evaluation Maneuvers (STEMs) provided repeatable tasks that could be compared with analytic linear and nonlinear simulation results. With suitable initial conditions and practice, gross acquisition and fine tracking could be performed at the desired angle of attack (AOA). Pilot comments indicated that these maneuvers were not consistent with the types of maneuvering performed during the close-in combat (CIC) evaluations. This testing identified problems that may not be significant in actual tasks. Further testing is needed to resolve these differences.

The pilot-assigned ratings for gross acquisition and fine tracking for both the longitudinal and lateral axes were dependent on AOA. More undesirable motions and then oscillations existed as AOA increased.

The longitudinal gross-acquisition task was well-defined and provided an easily repeatable task. The pilot ratings and comments indicated a high degree of confidence. These ratings reflected the expectations from CIC testing with the aircraft having Level 1 or Level 2 handling qualities.

The lateral gross-acquisition task was one of the most difficult. The task required a significant amount of flight time to adjust the starting conditions to achieve the desired AOA with the

target aircraft in the head-up display field of view for the X-31A airplane. The pilot proficiency for this task did not improve as significantly as it did for the other acquisition and tracking tasks. The pilot comments and ratings indicated a degradation in handling qualities as AOA increased, with Level 3 handling qualities at an AOA near 60°. The pilot comments noted that this type of acquisition was not similar to the acquisitions performed during CIC testing. The degradation in handling qualities was not expected from the CIC testing where the general assessment would have been Level 1/Level 2 handling qualities.

For the longitudinal fine-tracking task, consistent trends existed in regard to the Neal-Smith, bandwidth, and Smith-Geddes criteria. The maneuvers that received Level 1 ratings in flight were rated Level 1 by the criteria. The Levels 2 and 3 data from flight tended to produce consistent results when compared with the linear models and indicated potential modifications for the criteria. The X-31A handling qualities ratings showed a degradation with AOA that was not observed during the CIC testing.

Lateral fine tracking showed a degradation to Level 3 handling qualities as AOA increased. The X-31A program provided only a limited amount of data that could be compared with the existing criteria. The data showed good general agreement with the Smith-Geddes criterion. These data did not provide sufficient information to offer modifications to the existing criteria that predicted Level 1 or borderline Level 1/Level 2.

For both lateral and longitudinal fine tracking, the effect of the velocity-vector settling during the maneuver had a significant impact. Future use of this STEM may require modifications to allow a more stabilized starting condition for the fine-tracking tasks. During the X-31A testing, fully separating the lateral and longitudinal tasks was not possible. The pilots generally used diagonal stick inputs regardless of the axes being evaluated.

For control stick harmony, the majority of the comments were noted during the fine-tracking tasks. In these cases, the pilots were using diagonal stick inputs to perform the wing tip–to–wing tip and nose-to-tail tracking. The one other task that elicited a comment on control stick harmony was the combined maneuver. The pilot commented on the disparity in motion for longitudinal and lateral stick displacements (large for roll and small for pitch). Although the control implementation resulted in a limiter for large roll-stick deflection, no particular comments were given by the pilots.

The limited testing with the combined maneuver was commented upon favorably by the pilots, but these ratings are not amenable to comparison with analytic results because of the rapidly varying flight conditions. This type of maneuver may be useful for providing an overall evaluation of aircraft performance in the post-stall flight regime and should be considered as an additional STEM. Like the CIC results, these data are of limited value for analysis because of the varying flight conditions.

10. REFERENCES

[1]Sweeney, Joseph E. and Gerzanics, Michael A., "F-16 MATV Envelope Expansion: Testing For Controllable High AOA Maneuvering," *Society of Experimental Test Pilots Thirty-Eighth Symposium Proceedings*, Sept. 1994, pp. 285–295.

[2]Wichman, Keith D., "High Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, NASA Langley Research Center, Virginia, Sept. 17–19, 1996.

[3]Webster, Fredrick R. and Purifoy, Dana, *X-29 High Angle-of-Attack Flying Qualities*, AF-FTC-TR-91-15, Jul. 1991.

[4]U.S. Department of Defense, *Flying Qualities of Piloted Vehicles*, MIL-STD-1797, Mar. 1987.

[5]Krekeler, Gregory C., Jr., Wilson, David J., and Riley, David R., "High Angle of Attack Flying Qualities Criteria," AIAA-90-0213, Aug. 1990.

[6]Wilson, David J., Riley, David R., and Citurs, Kevin D., *Flying Qualities Criteria for 60° Angle of Attack*, NASA CR-4535, vol. I, Dec. 1993.

[7]Neal, T. Peter and Smith, Rogers E., *An In-flight Investigation to Develop Control System Design Criteria for Fighter Airplanes*, AFFDL-TR-70-74, vol. I, Dec. 1970.

[8]Smith, Ralph H., "The Smith-Geddes Criteria," *SAE Aerospace, Control & Guidance Symposium*, Reno, Nevada, Mar. 1993.

[9]Hoh, Roger H., Mitchell, David G., and Hodgkinson, John, "Bandwidth —A Criterion for Highly Augmented Airplanes," AGARD CP-333, Jun. 1982, pp. 9-1–9-11.

[10]Stoliker, P.C., *Simulation Prediction of High-Angle-of-Attack Handling Qualities for the X-31A*, NASA TM-4758, 1996.

[11]Cord, Thomas J., Leggett, David B., Wilson, David J., Riley, David R., and Citurs, Kevin D., "Flying Qualities Evaluation Maneuvers," AGARD CP-548, Mar. 1994, pp. 18-1–18-8.

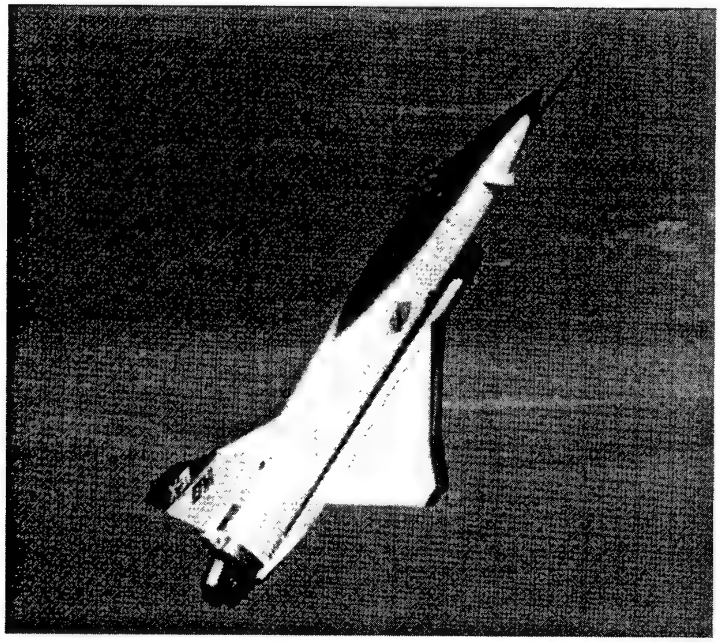
[12]Beh, H. and Hofinger, G., "X-31A Control Law Design," AGARD CP-548, Mar. 1994, pp. 13-1–13-9.

[13]Norlin, Ken A., *Flight Simulation Software at NASA Dryden Flight Research Center*, NASA TM-104315, Oct. 1995.

[14]Eubanks, D., Gütter, R., and Lee, B., "X-31 CIC Flight Test Results," *Four Power Senior Nation Representative Full Envelope Agility Workshop*, Eglin AFB, Florida, Mar. 1995.

[15]Cooper, George E. and Harper, Robert P., Jr., *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA TN-D5153, Apr. 1969.

[16]Foster, John V., Ross, Holly M., and Ashley, Patrick A., "Investigation of High-Alpha Lateral-Directional Control Power Requirements for High-Performance Aircraft," AIAA-93-3647, Aug. 1993.



EC 94-42478-1

Figure 1. X-31A airplane in poststall flight.

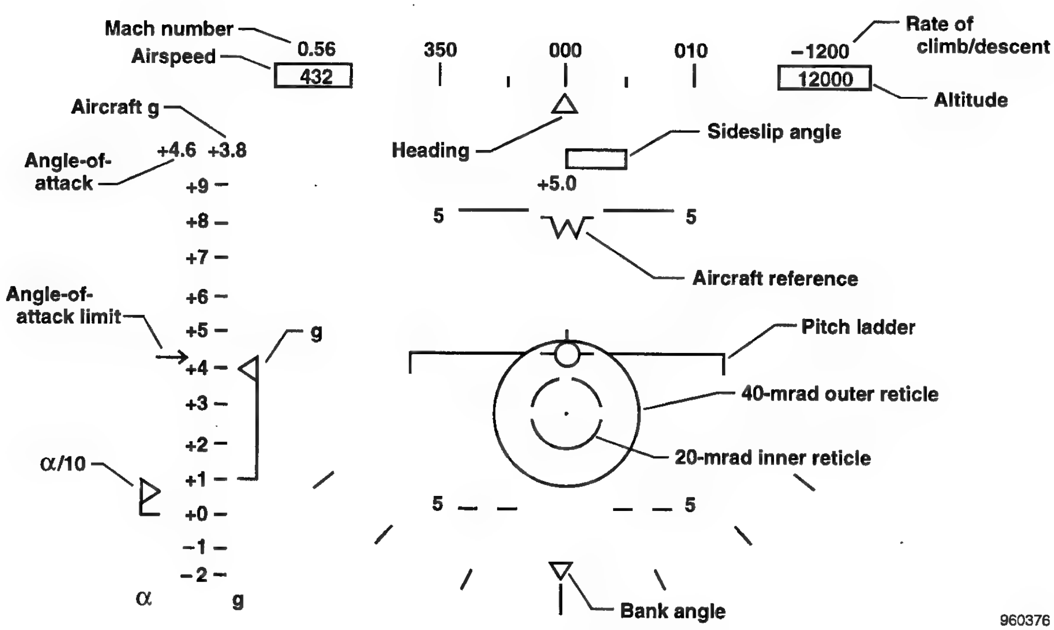


Figure 2. Head-up display symbology.

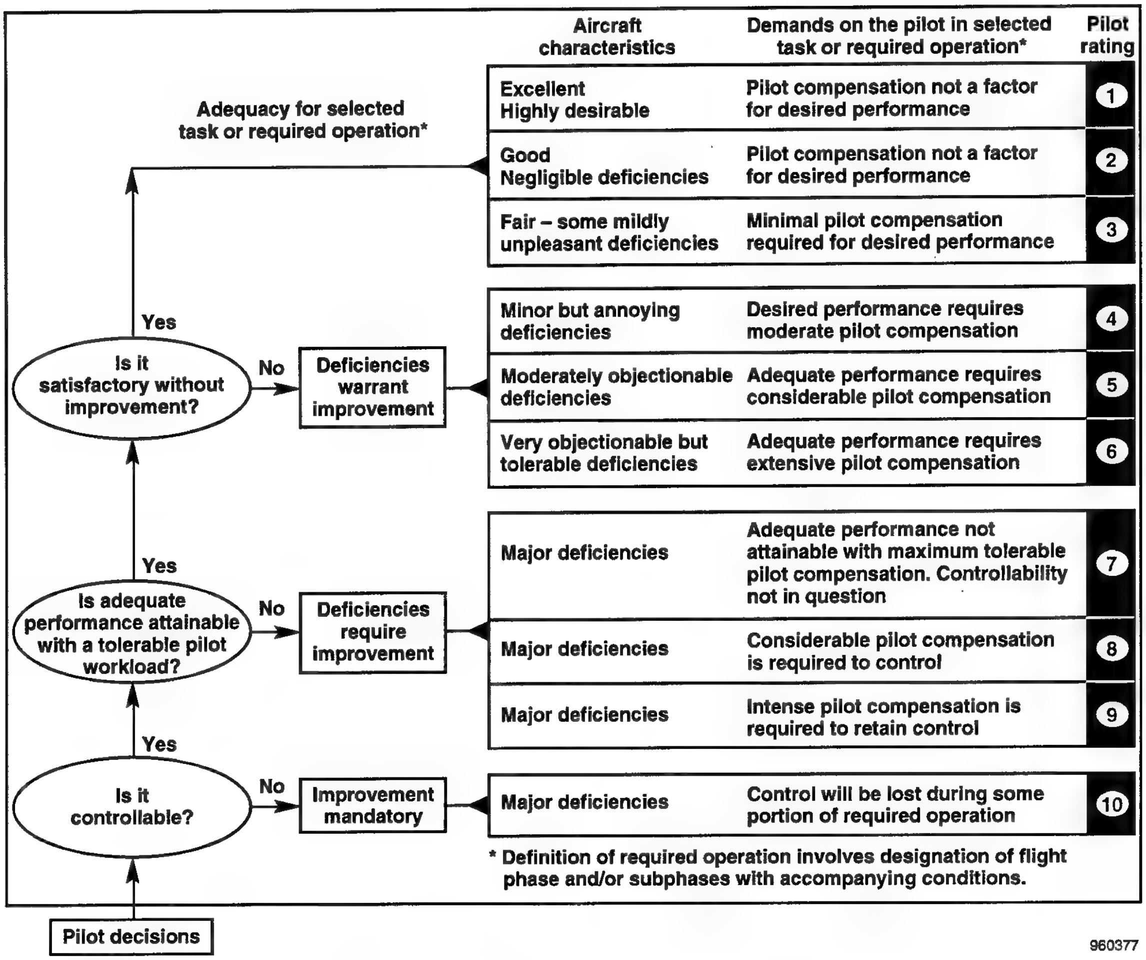


Figure 3. Cooper-Harper rating scale.

Classification	Description
A	The pilot rating was assigned with a high degree of confidence.
B	The pilot rating was assigned with only a moderate degree of confidence because of uncertainties introduced by moderate differences in environmental conditions, or in aircraft configuration or state, or in task, from what was desired.
C	The pilot rating was assigned with minimum confidence because of important differences between the desired and actual environmental conditions, aircraft configuration or state, or task, requiring considerable pilot extrapolation.

960378

Figure 4. Classification of pilot confidence factor.

Numerical rating	Description
1	No tendency for pilot to induce undesirable motions.
2	Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.
3	Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.
4	Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.
5	Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing stick.
6	Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing stick.

960379

Figure 5. Pilot induced oscillation rating scale.

Roll performance for mission effectiveness	Improvements in roll performance	Numerical
Enhancing – tactically superior	None warranted	1
Satisfactory – mission requirements met	May be warranted, but not required	2
Unsatisfactory – mission requirements not met	Required	3
Unacceptable – tactically useless	Mandatory	4

2.5

960380

Figure 6. Roll performance classification.

Desired:	Aggressively acquire target within 25* or 40** mrad longitudinally of pipper with no overshoot and within a desirable time to accomplish the task.
Adequate:	Aggressively acquire the target within 25* or 40** mrad longitudinally of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.

* Criterion for 30°and 60° AOAs ** Criterion for 45° AOA

960381

Figure 7. Performance criteria for longitudinal gross acquisition.

Desired:	Aggressively acquire target within 25* or 40** mrad laterally of pipper with no overshoot and within a desirable time to accomplish the task.
Adequate:	Aggressively acquire the target within 25* or 40** mrad laterally of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.

* Criterion for 30° AOA ** Criterion for 45° and 60° AOAs

960382

Figure 8. Performance criteria for lateral gross acquisition.

Desired:	**Pipper within +/– 5 mrad band for 50 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**
Adequate:	**Pipper within +/– 5 mrad band for 10 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**

960383

Figure 9. Performance criteria for fine-tracking tasks.

Gross acquisition	**Desired:**	**Aggressively acquire target within 25 mrad of pipper with no overshoot and within a desirable time to accomplish the task.**
	Adequate:	**Aggressively acquire the target within 25 mrad of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.**
Fine tracking	**Desired:**	**Pipper within +/– 5 mrad band for 50 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**
	Adequate:	**Pipper within +/– 5 mrad band for 10 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**

960384

Figure 10. Performance criteria for the combined maneuvers.

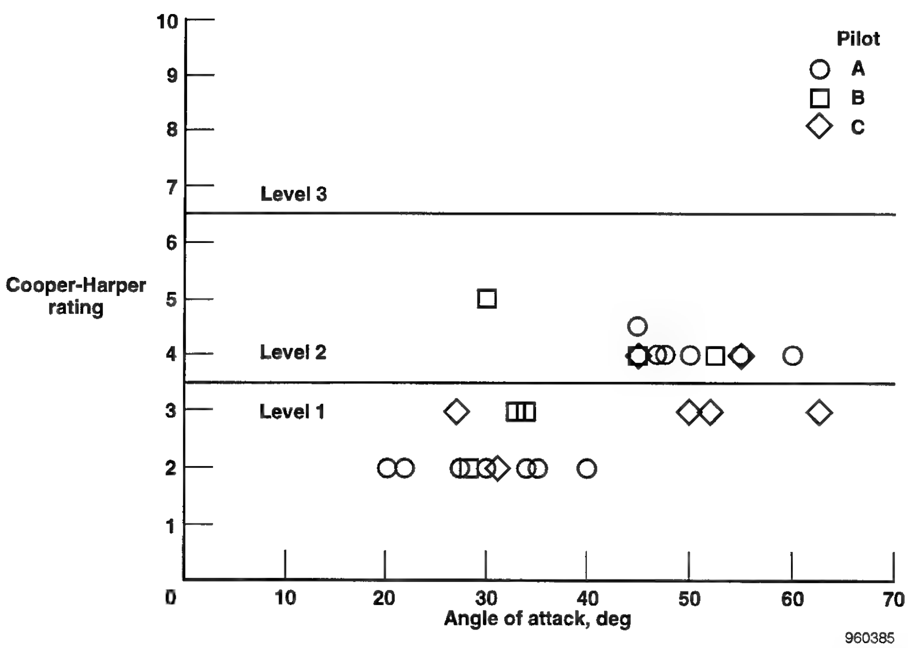


Figure 11. Cooper-Harper ratings as a function of angel of attack for longitudinal gross acquisition.

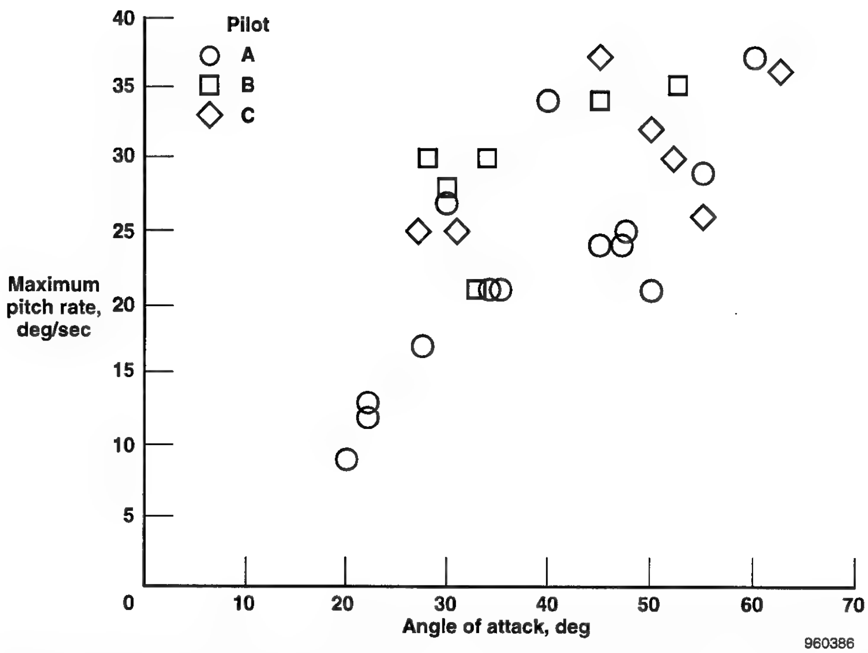


Figure 12. Maximum pitch rate as a function of angle of attack for longitudinal gross acquisition.

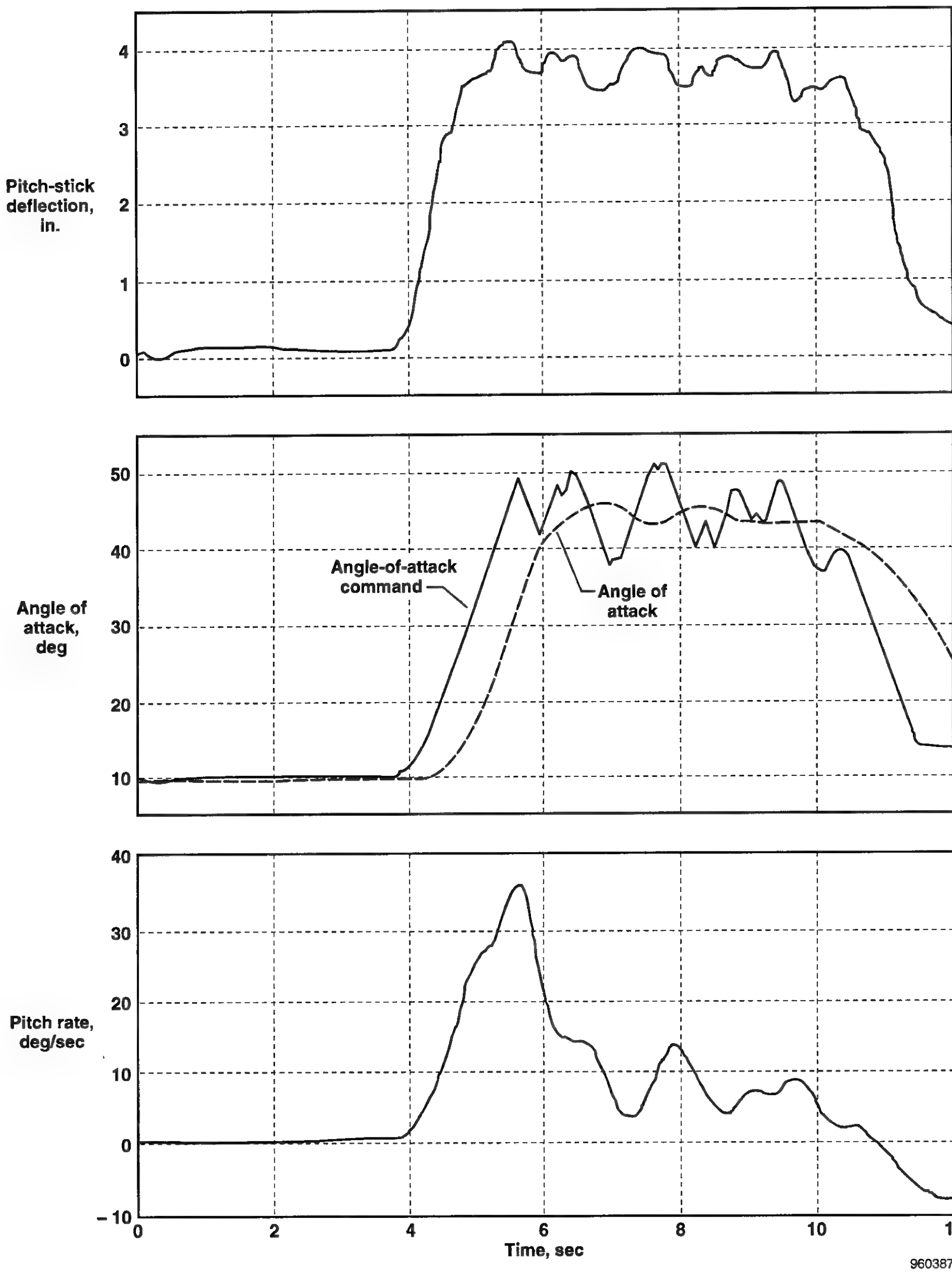


Figure 13. Time history from longitudinal gross acquisition.

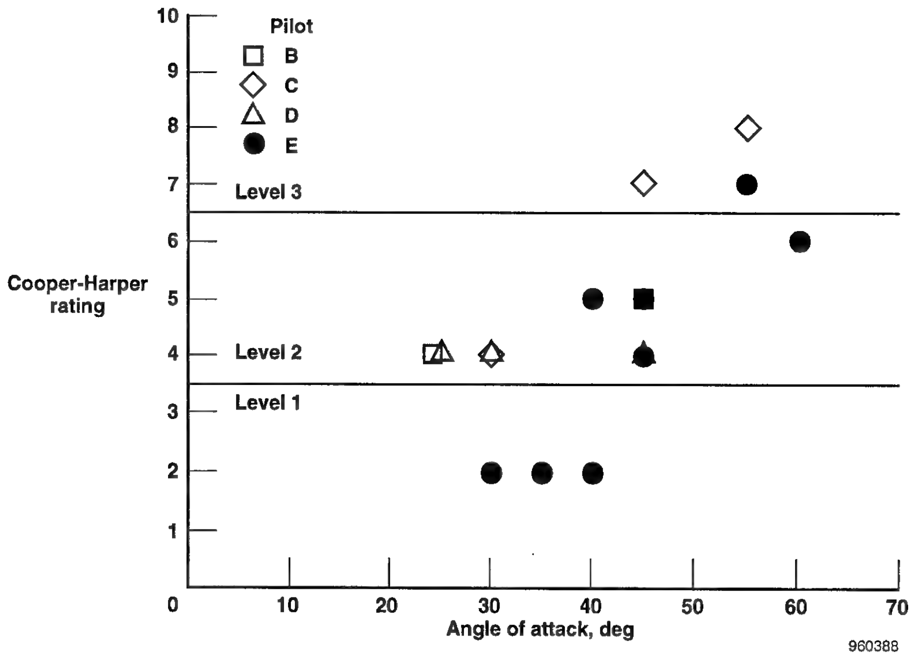


Figure 14. Cooper-Harper ratings as a function of angle of attack for lateral gross acquisition.

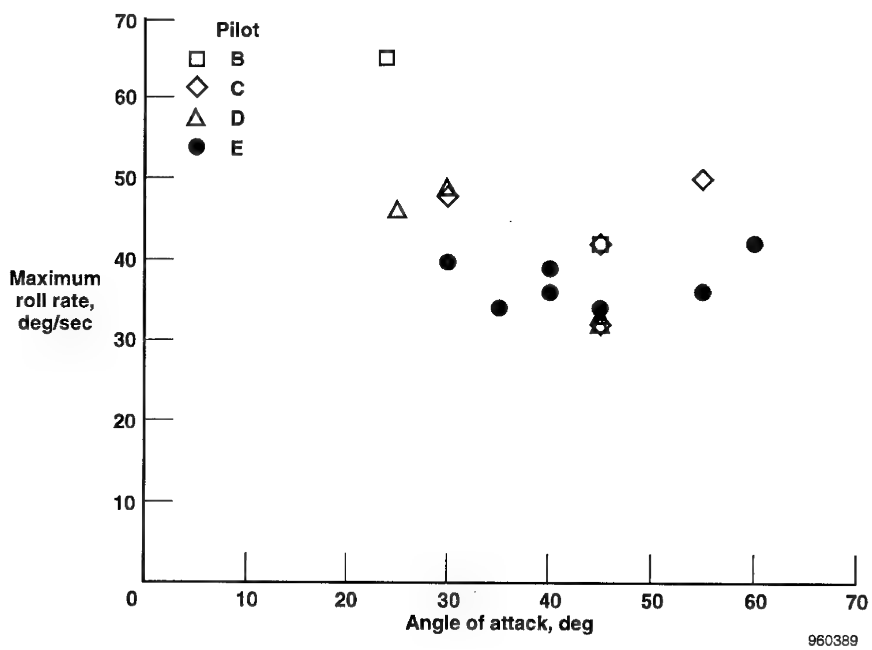


Figure 15. Stability-axis roll rate as a function of angle of attack for lateral gross acquisition.

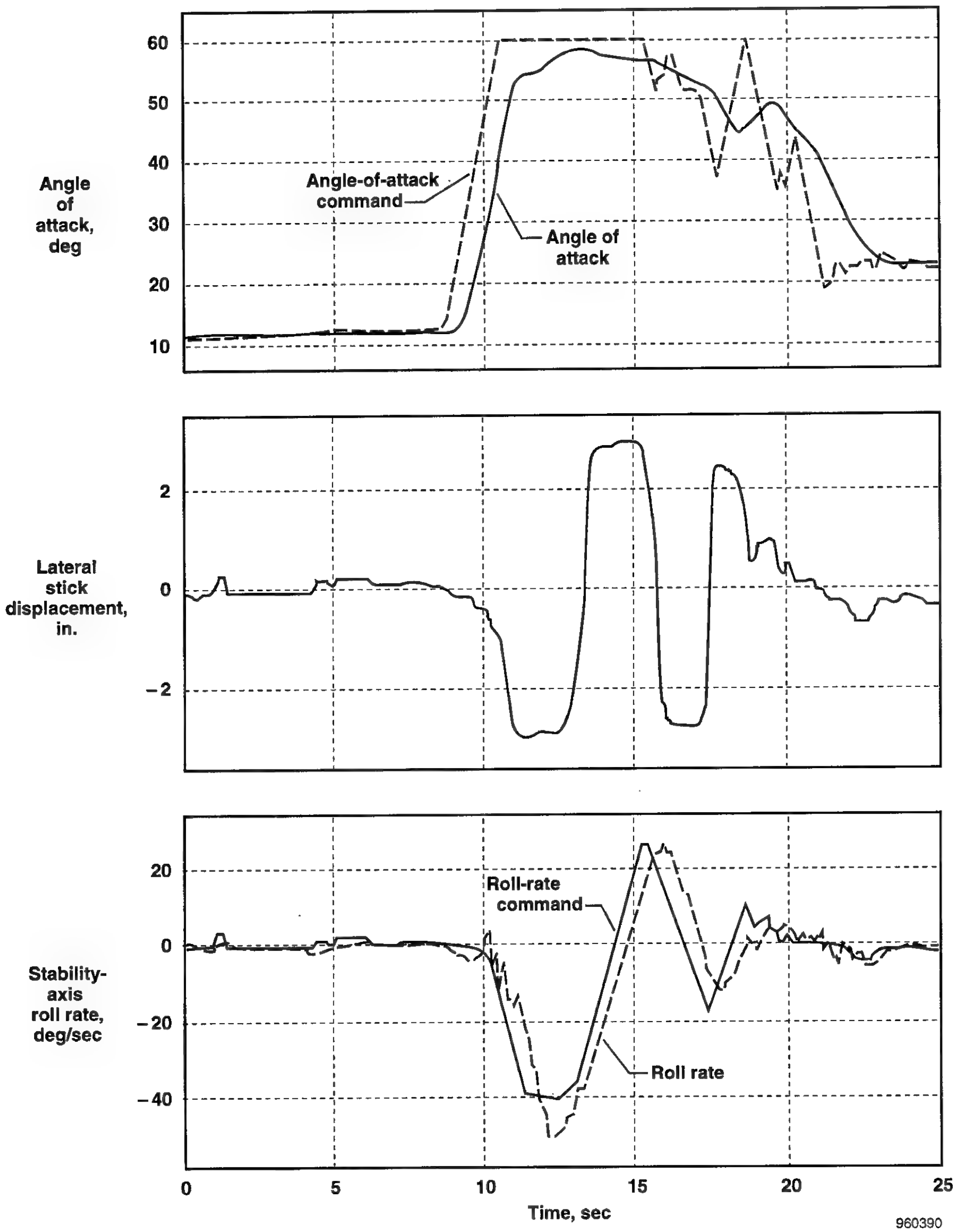


Figure 16. Time histories for lateral gross acquisition.

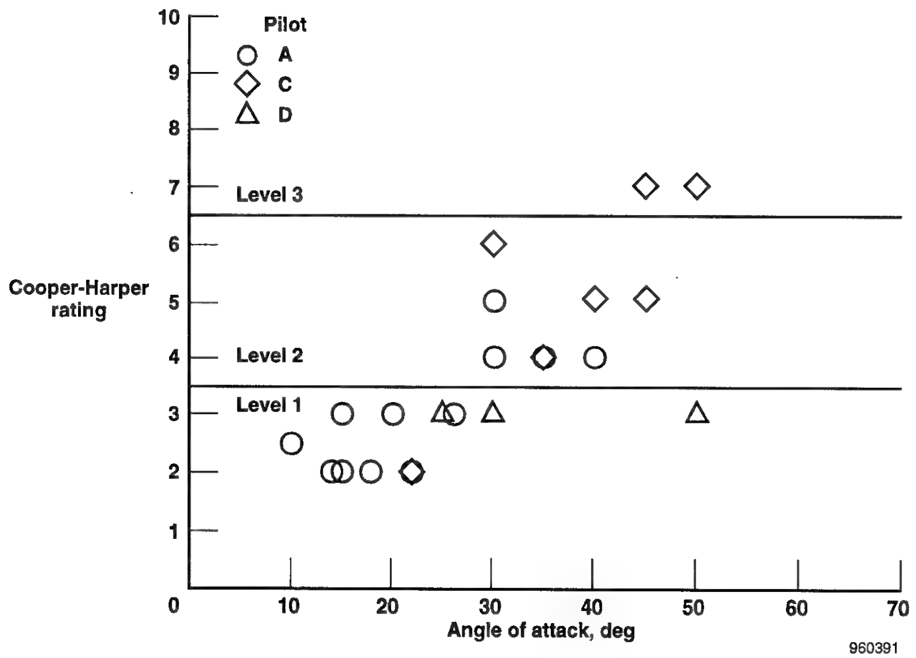


Figure 17. Cooper-Harper ratings as a function of angle of attack for longitudinal fine tracking.

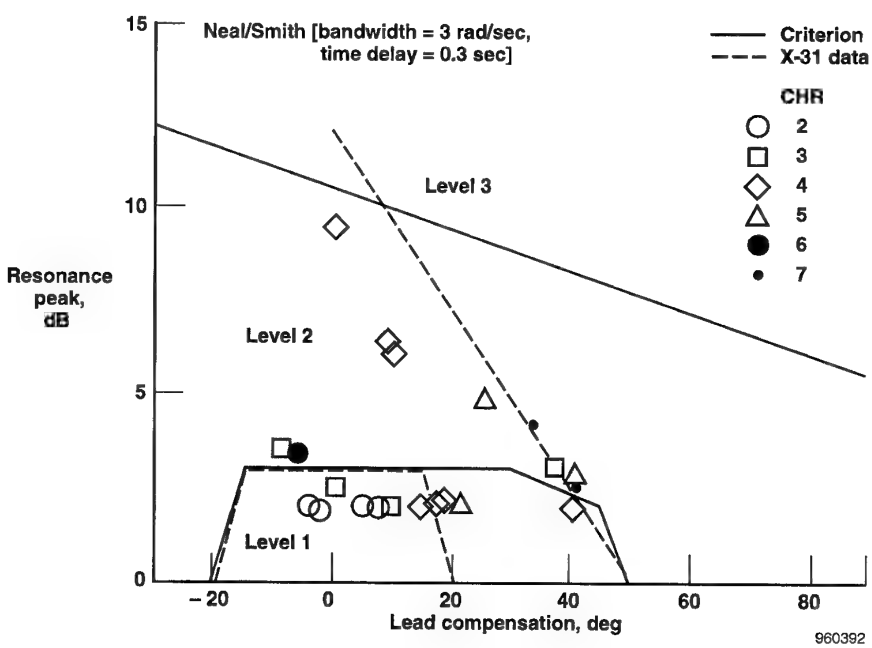


Figure 18. Comparison of X-31A data with the Neal-Smith criterion.

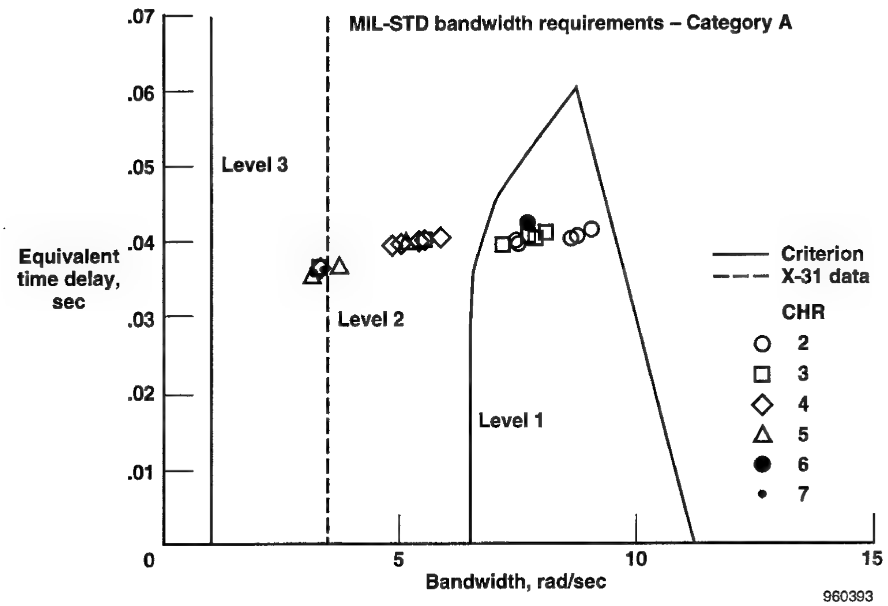


Figure 19. Comparison of X-31A data with the bandwidth criterion.

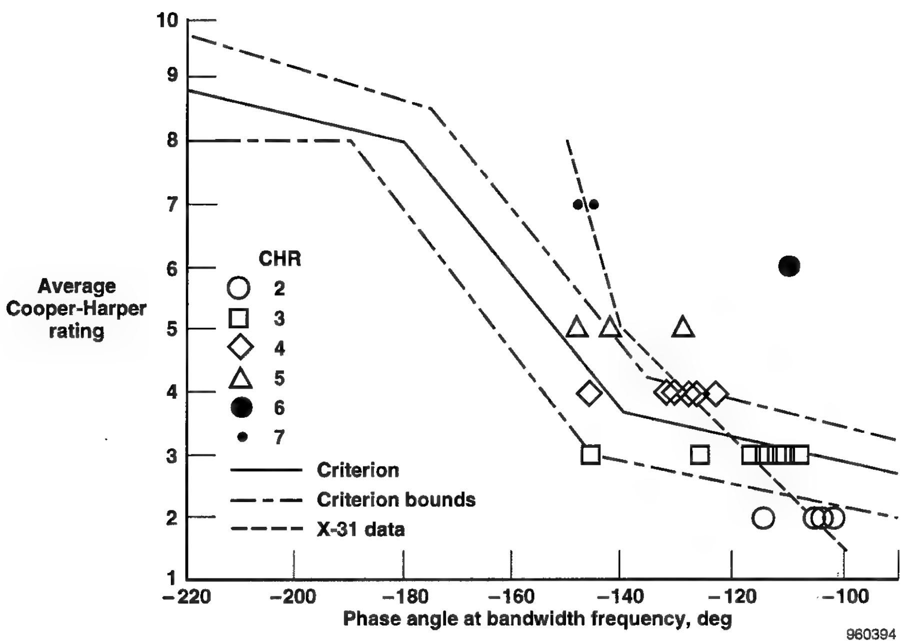


Figure 20. Comparison of X-31A data with the Smith-Geddes criterion.

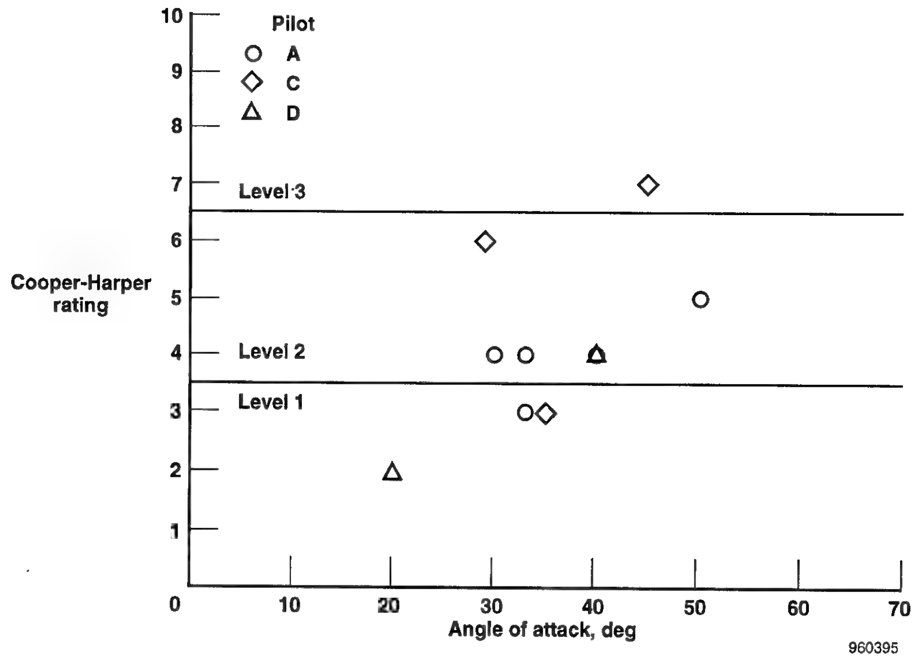


Figure 21. Cooper-Harper ratings as a function of angle of attack for lateral fine tracking.

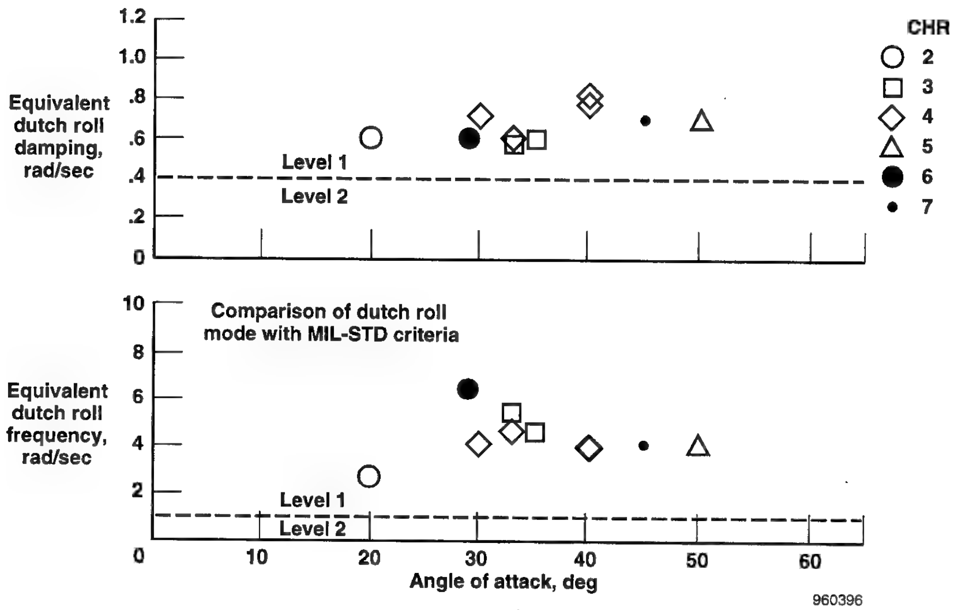


Figure 22. Comparison of X-31A data with MIL-STD-1797 dutch roll frequency and damping criteria.

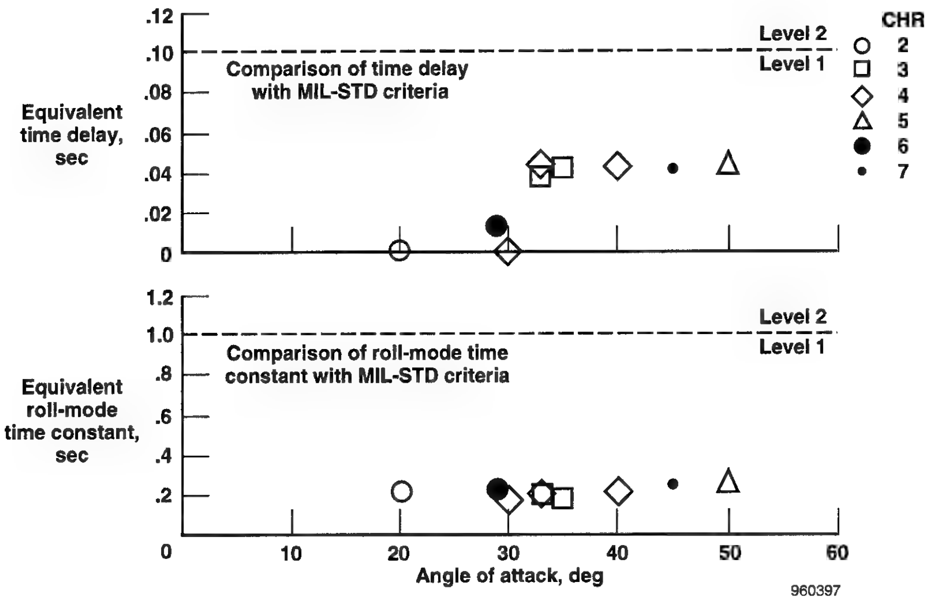


Figure 23. Comparison of X-31A data with MIL-STD-1797 roll mode time constant and time delay criteria.

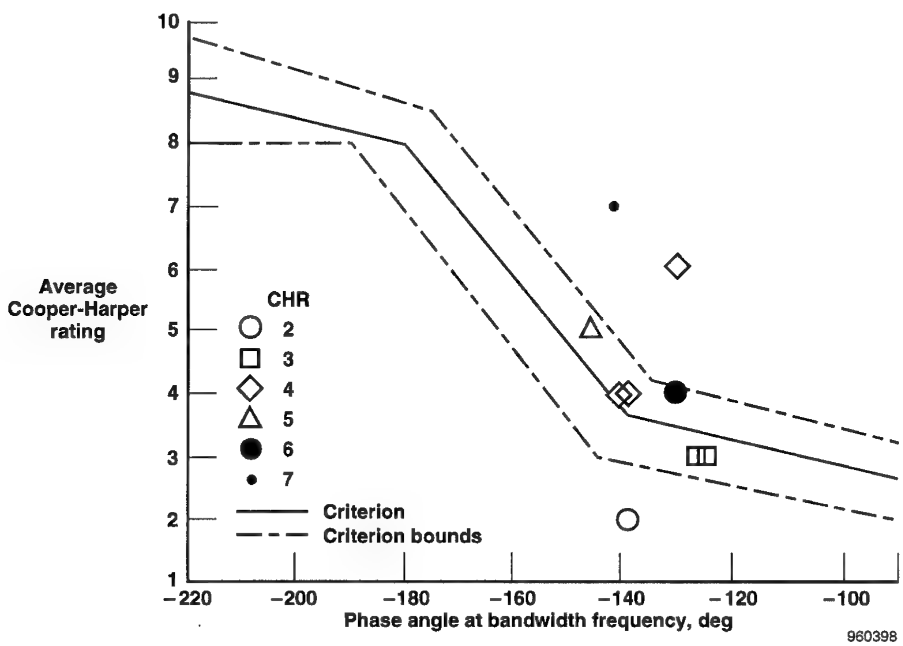


Figure 24. Comparison of X-31A data with Smith-Geddes criteria for the lateral axis.

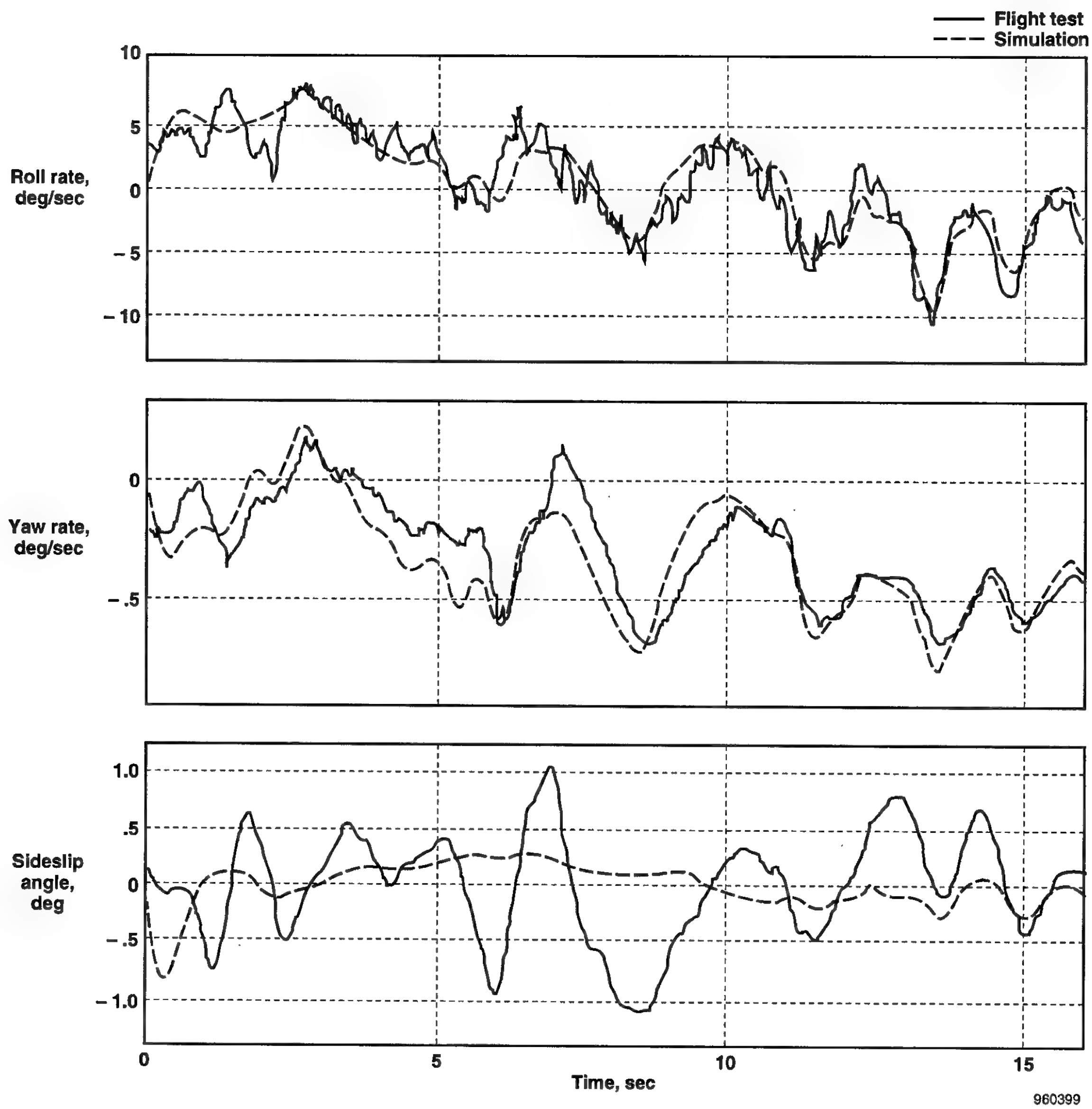


Figure 25. Comparison of flight and simulation data for a lateral fine-tracking case.

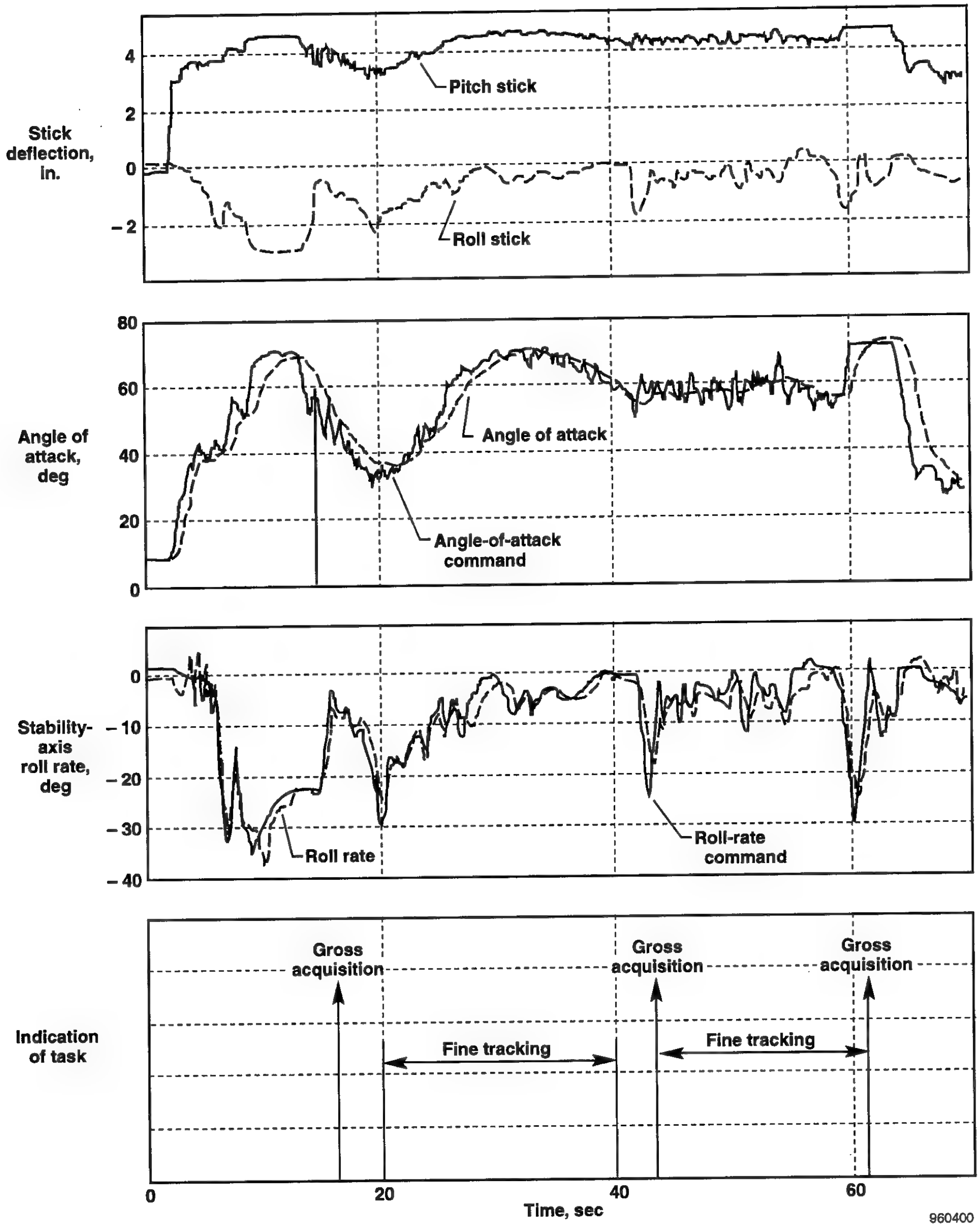


Figure 26. Time history from a combined maneuver.

X-31A TACTICAL UTILITY FLIGHT TESTING

Holger Friehmelt
DLR
Institute of Flight Mechanics
P.O. Box 32 67
D-38022 Braunschweig, Germany
eMail: Holger.Friehmelt@dlr.de

Quirin Kim
Bundesluftwaffe
Stab JG 74
Wilhelm-Franke-Kaserne
D-86633 Neuburg / Donau, Germany

Richard Gütter
Daimler-Benz Aerospace AG
LMLE2
P.O. Box 80 11 60
D-81663 München, Germany
eMail: Richard.Guetter@dasa.dbmail.dbp.de

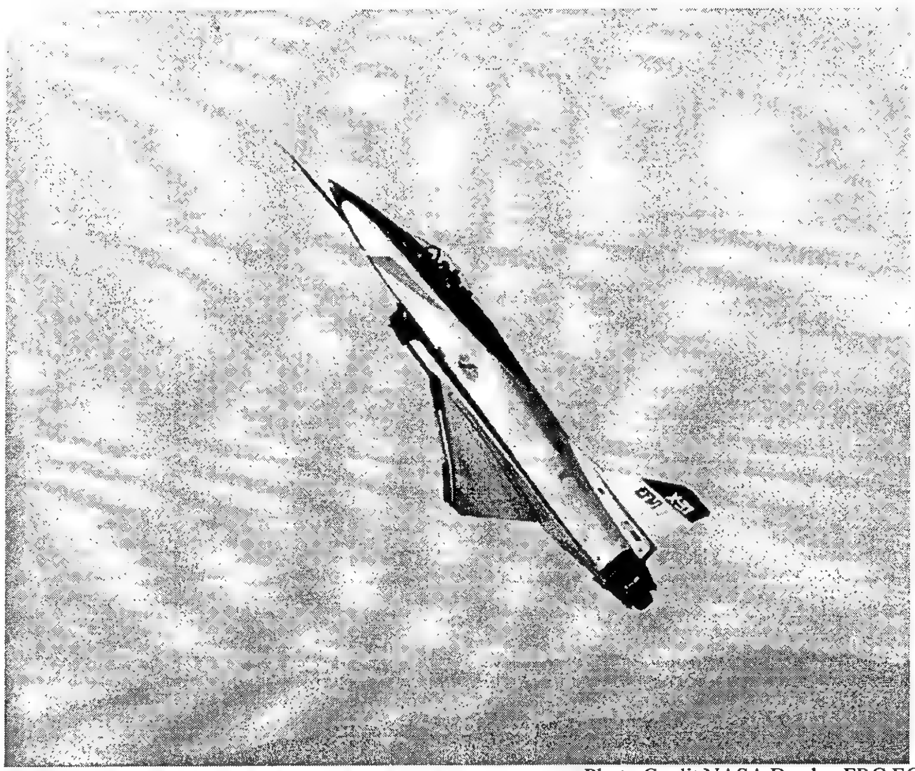


Photo Credit NASA Dryden FRC EC94-42478-16

Figure 1: X-31A Flying at 70° AoA over Edwards AFB, CA

1. ABSTRACT

The two X-31A were jointly built by Daimler-Benz Aerospace AG and Rockwell International. These German-American experimental aircraft were designed to explore the new realm of flight far beyond stall by employing advanced technologies like thrust vectoring and sophisticated flight control systems. The X-31A aircraft is equipped with a thrust vectoring system consisting of three aft mounted paddles to deflect the thrust vector in both pitch and yaw axes, thus providing the X-31A in this *'Enhanced Fighter Maneuverability'* program with an agility and maneuverability never seen before. The tactical utility of the X-31A using post stall technologies has been revealed in an extensive flight test campaign against various current state-of-the-art fighter aircraft in a close-in combat arena. The test philosophy included both simulation and flight test. The tremendous tactical advantage of the X-31A during the tactical utility evaluation flight test phase was accompanied by a deepened insight into post stall tactics, its typical maneuvers, impacts on pilot-aircraft interfaces and requirements for future weapons to both engineers and the military community. Some selected aspects of the tactical utility of the X-31A using post stall technologies unveiled by the International Test Organization are presented here.

2. NOMENCLATURE

AFB	Air Force Base
AGL	Above Ground Level
AoA	Angle of Attack
ARPA	Advanced Research Projects Agency
BVR	Beyond Visual Range
CIC	Close-in-Combat
Dasa	Daimler-Benz Aerospace AG
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
ECM	Electronic Counter Measures
EF	EuroFighter
EFM	Enhanced Fighter Maneuverability
FMOD	Federal Ministry of Defense
HUD	Head-Up Display
IABG	Industrie- und Anlagenbau Gesellschaft
IFF	Identification Friend Foe
ITO	International Test Organization
MBB	Messerschmidt Bölkow Blohm
MIL	Milli-Radian
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
PST	Post Stall
QT	'Quasi-Tailless'
TES	Test and Evaluation Squadron

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

TKF Taktisches Kampfflugzeug
TU Tactical Utility
USAF United States Air Force
USN United States Navy
WTD Wehrtechnische Dienststelle
WVR Within Visual Range

C_L Lift Coefficient
g Gravitational Acceleration
L Lift
m Mass
n_z Load Factor
P_S Probability of Survival
r Turn Radius
S Wing Surface Area
V Air Speed
α Angle of Attack
χ Heading Angle
ρ Air Density

3. INTRODUCTION

The X-31 program was dedicated to explore the controlled flight beyond stall and enhanced agility (supermaneuverability) [1] with experimental aircraft. Thrust vectoring in both pitch and yaw axes was used for the first time as well as the X-31A was the first experimental aircraft in the famous series of X-Planes being developed and tested internationally involving both Germans and Americans [2]. The X-31A aircraft impressively demonstrated superior short range air combat capabilities by means of poststall technologies as is described in the following. The tactical utility (TU) flight testing at NASA Dryden Flight Research Center revealed the X-31A being superior to any existing fighter aircraft in terms of the ability to make tight and quick turns and any measures of agility. Most of this unique agility can be attributed to the thrust vectoring system.
The concept of supermaneuverability was originated about 1978 by the late DR. WOLFGANG B. HERBST of MBB [3]. It was in response to the development of short range air-to-air missiles with all aspect capabilities that a new area of tactics of aerial combat evolved. The ability to successfully launch a missile in almost any clockwise position against an opponent has altered the tactics of air combat and thus the performance requirements of fighter aircraft.

3.1 Test Philosophy

Figure 2 depicts the test philosophy chosen to achieve the objective *'to investigate the tactical benefits of enhanced fighter maneuverability'*. It incorporated of four main blocks.

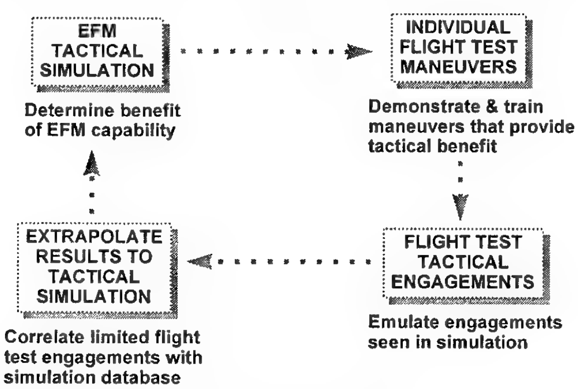


Figure 2: Test Philosophy to Investigate EFM

The plan established for demonstrating the tactical utility of the X-31A consisted of tactical simulation exercises, which demonstrated the tactical benefits of EFM and generated a database of a statistically significant number of close-in combat engagements. From this database, tactically useful EFM maneuvers could be isolated to be demonstrated and trained in actual flight. Mock CIC engagements were then flown with the anticipation of achieving results seen previously in simulation.
The final step of the test philosophy was to correlate the limited number of flight test engagements back to the larger simulation database.

3.2 Simulation

Extensive manned and digital air combat simulations revealed that appropriate tactics actually would result in mutual head-on launch opportunities and thus the dilemma of potential mutual kills of almost equal high performance fighters. The analysis of such engagements unveiled a new maneuver cycle characterized by dominance of instantaneous maneuvers and a tendency to slow speed.

3.3 Turn Performance

At slow speed V an aircraft can achieve a smaller turn radius r at a given turn rate $\dot{\chi}$ as shown by Equation (1):

$$r = \frac{V}{\dot{\chi}} \tag{1}$$

The turn radius is proportional to the square of the speed since turn rate can be written in terms of speed and possible load factor n_z

$$\dot{\chi} = \frac{g}{V} \cdot \sqrt{n_z^2 - 1} \tag{2}$$

which yields with Equation (1):

$$r = \frac{V^2}{g} \cdot \frac{1}{\sqrt{n_z^2 - 1}} \quad \Rightarrow \quad r \sim V^2 \tag{3}$$

Thus, low speed in a turn can drastically decrease the required turn radius while the maximum load factor is usually already limited by capabilities of the air crew.
Obviously, a tighter turn in a developing mutual head-on situation allows for an earlier weapon launch opportunity at any given off-boresight angle. Figure 3 depicts the relationship between turn radii and speed for load factors between 2 and 6.

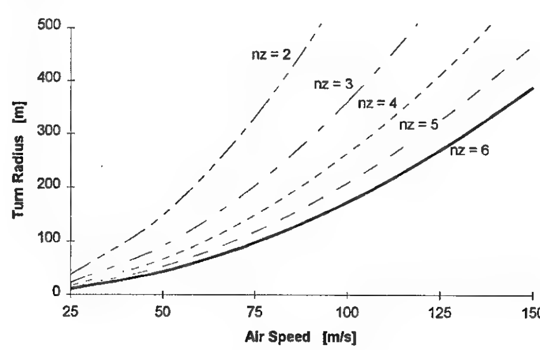


Figure 3: Turn Radii vs. Speed

4. EVOLUTION OF CLOSE-IN-COMBAT TACTICS

The evolution of close-in-combat (CIC) tactics as anticipated by SKOW [4] already before the X-31A tactical utility results became public and manifested his conclusions is depicted in Figure 4.

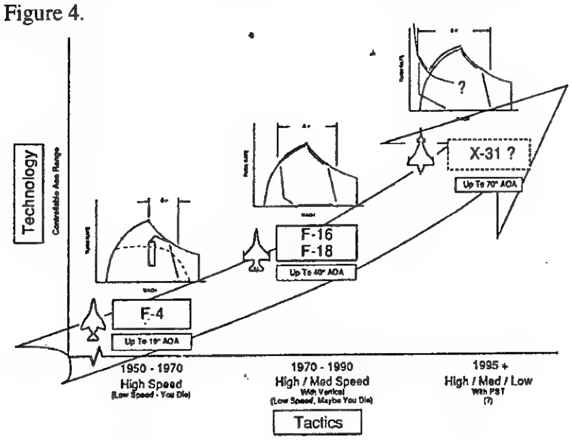


Figure 4: Evolution of CIC Tactics [4]

Aircraft like the F-4 were limited to angles of attack of up to 19°. Flight at higher angles of attack often resulted in departures. Furthermore, due to the high wing loading of the F-4, maneuvering at high angles of attack for prolonged times resulted in a significant loss of energy and placed the pilot in an unfavorable position with limited options. Thus it is easy to understand why phrases like *'Low Speed - You Die'* and *'Speed is Life'* were commonly used to characterize CIC tactics in the period from roughly 1950 to 1970. Modern fighter aircraft like the F-16 and F/A-18 with angle of attack capabilities of up to 40° allowed to turn at lower speeds as shown by the insets of the doghouse plots (turn rate vs. Mach number) in Figure 4. Fighter pilots started to use the vertical and the old maxims changed to *'Low Speed, Maybe You Die'*. Low wing loading limited the bleeding of energy during aggressive maneuvering and guaranteed a multitude of offensive and defensive options to the pilot. With the advent of deep post stall capabilities by the X-31A again a new area of CIC tactics has begun. Maneuvers can now be performed at extremely low speeds as indicated by the doghouse plot in Figure 4.

The present paper will now describe the X-31A tactical utility flight test phase highlighting some aspects and results of the X-31A tactical utility using post stall technologies. First however, some conclusive arguments why CIC can still develop in a time of highly sophisticated stealth aircraft and advanced beyond visual range (BVR) weapon systems including both sensors and weapons will be given.

The X-31A configuration and its performance capabilities are then briefly introduced including its flight test envelope and head-up display. Main emphasis however is on the tactical utility flight test phase. Its build-up, starting conditions, selected measures of effectiveness are discussed as well as some representative results are presented.

Two post stall maneuvers, the clinical 'Herbst Maneuver' and a post stall maneuver resembling a 'fire pole' will be described. For more detailed results of the various phases of the tactical utility flight test program and an extensive collection of post stall maneuver descriptions the reader may refer to various references of different classification levels [5, 6, 7].

5. CIC IN THE AIR COMBAT CONTINUUM

An implicit assumption justifying X-31A TU flight testing was that for many reasons future air combat will still develop into CIC and won't be restricted to BVR engagements. Although it will always be desired to engage targets already from BVR, some reasons for the development of CIC are:

- The dynamic merge during prolonged engagements will eventually bring the aircraft close together.
- Measures to enhance low observability may conceal aircraft until they are detected visually in a CIC regime.
- Various optical and electronic counter measures (ECM) can limit sensors in their ability to detect aircraft BVR.
- Limits on number and types of stores carried as well as failed missiles may drive aircraft into a CIC arena.
- Special rules of engagement especially concerning target identification, i.e. identification friend foe (IFF), requirements can make an approach into CIC necessary.
- And last but not least fighting outnumbered, surprised, or having to defend fixed assets on the ground may require to engage into CIC.

These assumptions are tacitly validated by the fact that even the newest air-to-air fighters are all equipped with a gun.

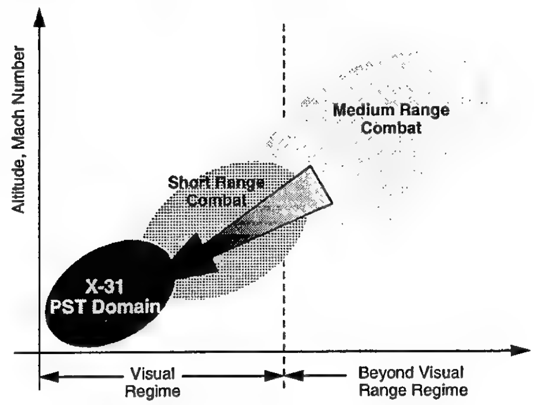


Figure 5: Arenas of Aerial Combat

To retain flexibility and adaptability in combat, fighters must be able to engage at will and dominate across the entire combat continuum as shown in Figure 5. Within visual range (WVR) and CIC engagements should not be favored over BVR, but if forced into CIC, enhanced fighter maneuverability (EFM) provides the necessary potential to effectively and successfully engage. It is here where the X-31A TU flight testing uncovered new dimensions of aerial combat.

6. X-31A CONFIGURATION

The two X-31A aircraft were developed, designed, and built jointly by Rockwell International and Daimler-Benz Aerospace One design driver for the X-31A configuration was the requirement that results of X-31A flight testing should be directly transferable to a potential operational aircraft. However, no existing fighter aircraft was suitable to be retrofitted for supermaneuverability. Eventually a derivation of the German TKF (Taktisches Kampfflugzeug), a predecessor of the EF2000, was selected. Figure 6 shows a three-dimensional view of the X-31A configuration as it meets all requirements for enhanced fighter maneuverability.

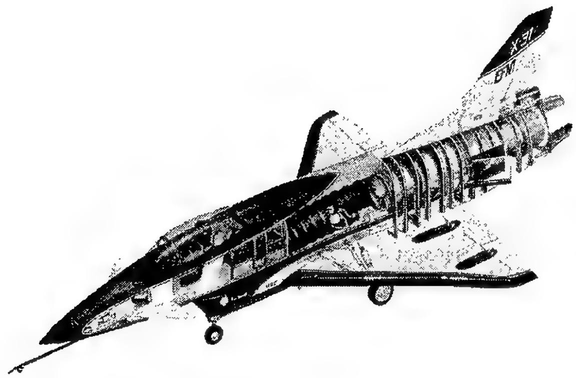


Figure 6: X-31A Configuration

The single-seat fighter-type X-31A is a delta-wing configuration with a long-coupled canard. Its take-off weight is little over 16 000 lbs. The X-31A is powered by a single General Electric F404 engine with some 17 000 lbs thrust wet. In order to reduce trim drag in supersonic flight the X-31A was designed with a center of gravity aft of the subsonic center of lift which makes it aerodynamically unstable. As the canard is commanded downward into the wind with increasing angle of attack it always maintains its control effectiveness (see [8] for selected aerodynamic identification results) and can be utilized for longitudinal control throughout the flight envelope. It especially guarantees adequate pitch-down control power in PST flight. Other control surfaces of the X-31A include a rudder and ailerons, i.e. trailing edge flaps which can be used both as elevator and ailerons. Unique feature of the X-31A are its three aft mounted paddles around the exhaust nozzle of the engine. These carbon-carbon paddles allow a deflection of the thrust vector in both pitch and yaw axis thus providing means of enhanced longitudinal and lateral/directional control independent from dynamic pressure and angle of attack as compared to the conventional aerodynamic control surfaces [9]. Summarizing the features of the X-31A configuration it is clear that the requirements for an aircraft with supermaneuverability were met:

- The thrust-to-weight ratio is in excess of 1.
- The air intake allows full power engine operation at up to 70° angle of attack by a movable intake lip.
- Aerodynamic characteristics have been tailored to enable a smooth transition into the PST regime.
- Thrust vectoring in pitch and yaw adds a vast amount of control power in those axes while the X-31A is still trimable by conventional aerodynamic control surfaces even at PST angles of attack. Thus the thrust vectoring system is no safety critical item in terms of recovery from a possible spin entry.

To control the X-31A a full authority, triplex, digital fly-by-wire flight control system has been developed by Dasa [10]. It includes mechanization of lateral stick inputs to roll the aircraft around the flight path at zero sideslip rather than around the familiar aircraft body axes. Thus, the so-called 'velocity vector roll' is a coordinated yaw and roll maneuver in terms of body axes. The longitudinal control features angle of attack command at slow speeds and load factor command at higher speeds. One of the main tasks of the flight control system is the scheduling of control surfaces and thrust vector blend-in dependent on their control effectiveness as a function of flight condition.

6.1 Head-Up Display

The X-31A was equipped with a head-up display (HUD). Its symbology is shown in Figure 7. Explaining most of the indicators and dials on the HUD, the unique performance features of the X-31A are illustrated again.

On the left hand side is an angle of attack ladder and a digital display. Range of values of the AoA ladder is -20° ... 90° while the maximum AoA which can be commanded at lower dynamic pressures is 70°. Inboard of the AoA ladder is a load factor ladder with an additional digital display. At higher dynamic pressures n_Z is commanded by the pilot instead of a. Maneuvers in deep post stall are maneuvers at extremely low speed and thus the load factor during those maneuvers is moderate. In the upper right-hand corner altitude above ground as well as rate of climb / descent are displayed digitally. All TU flight testing at Edwards AFB was performed in designated spin areas above 13 000 ft MSL respectively some 3 200 m above ground level (AGL). The rules of engagements called for an immediate 'Knock it off' command by either the control room or any of the pilots in case of an altitude violation.

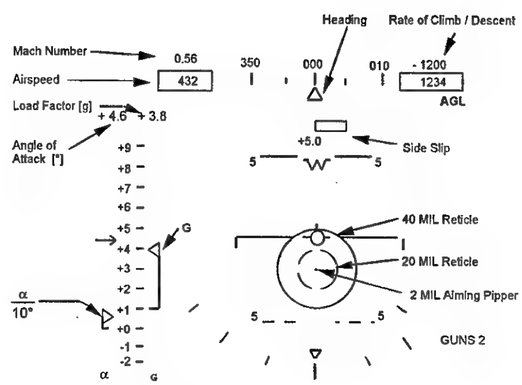


Figure 7: HUD of the X-31A

Although a hypothetical sideslip angle of 5.0° is indicated in Figure 7 digitally and by a bar in the middle of the HUD, the X-31A flew without any major sideslip thanks to its control law design except during cross wind landings and deliberate sideslip maneuvers. There is no need to use the pedals for any but those two reasons. Two reticles of 40 and 20 MIL and a 2 MIL gun aiming pipper formed the center of the HUD. The gun aiming line was depressed by 2° from the aircraft's center line. Video footage of the HUD camera provided valuable information for post flight analyses of the CIC engagements.

The pilot could select various levels of declutter of the HUD as desired. In addition to the HUD, a helmet mounted display was investigated [11].

7. TACTICAL UTILITY EVALUATION

7.1 TU Envelope

Figure 8 shows the flight envelope of the X-31A used during the tactical utility evaluation phase. It is a subset of the cleared flight envelope which also includes supersonic flight regimes and higher post stall entry speeds.

It is noteworthy that the flight control system of the X-31A provides carefree handling qualities throughout the flight envelope [12, 13]. Thus, the pilots weren't exposed to any additional workloads especially in post stall concerning possible departures and spin entries.

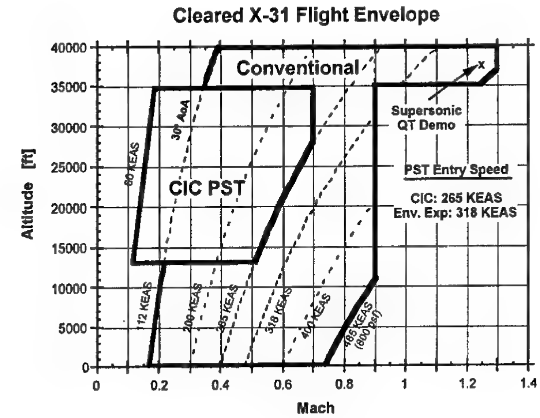


Figure 8: X-31A Envelope for CIC

7.2 Measures of Effectiveness

It is very difficult to conclusively describe the agility of the X-31A and its tactical implication on the outcome of CIC. Looking at a definition of agility by Skow [4] it becomes obvious that no known metrics cover the entire weapon system in all aspects: *'Agility is an attribute of a fighter aircraft that measures the ability of the entire weapon system to minimize the time delay between target acquisition and target destruction.'*

Although a multitude of primary and secondary measures of effectiveness were evaluated during the X-31A TU flight testing, only selected results of two primary measures are given in this paper.

The exchange ratio is defined as the ratio of adversary losses divided by the number of own losses.

$$\text{Exchange Ratio} = \frac{\text{Number of Adversary Losses}}{\text{Number of Own Losses}} \qquad (4)$$
$$\text{Exchange Ratio} \in [0,\infty]$$

The range of values of the exchange ratio is from 0 to infinity indicating a superior adversary and own superiority, respectively. An exchange ratio of 1.0 or 1:1 as the fractions sometimes aren't simplified represents an equal number of adversary losses and own losses.

The S Factor is calculated from the probability of survival of the adversary and one's own.

$$\text{S Factor} = 0.5+0.5\left(P_{S_{Own}} - P_{S_{Adversary}}\right) \qquad (5)$$
$$\text{S Factor} \in [0,1]$$

The probability of survival is defined by

$$P_S = \frac{\text{Number of Engagements Survived}}{\text{Total Number of Engagements}} \qquad (6)$$

Thus an S Factor of 0 represents 100% own losses while all adversary aircraft survive. An S Factor of 0.5 is equivalent to an exchange ratio of 1:1.

A compilation of various measures of effectiveness and agility metrics is given in [14], a comprehensive description of mathematical methods including measures of effectiveness in defense analyses in [15].

7.3 Starting Conditions

In order to efficiently perform TU flight testing, a set of starting conditions was selected. They were chosen to maximize the results by guaranteeing easy repeatability and to quickly force the engagements into CIC, the objective of all X-31A TU flight tests. Only by this way could the most be gained from a limited number of sorties.

The starting conditions investigated included defensive, offensive, and various types of neutral set-ups. All starting conditions are depicted in Figure 9.

While the defensive, offensive, and line-abreast starting conditions were also investigated in simulation studies [16], the butterfly set-up was introduced by USAF and USN guest pilots during a special TU flight test campaign.

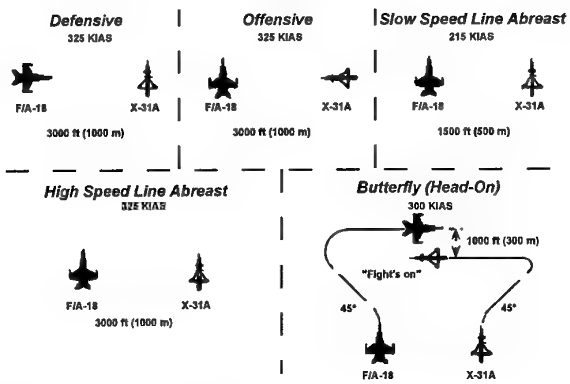


Figure 9: Starting Conditions

8. TACTICAL UTILITY FLIGHT TESTING

As one of the main X-31 EFM Program objectives a tactical utility evaluation phase was conducted between October 1991 and October 1995. Leading the way to TU flight testing were two X-31 EFM simulation campaign conducted at the IABG facility in Ottobrunn, Germany, between October 1991 and April 1993 [16]. These simulation campaigns were used to define test methods and baseline expectations in a phased build-up approach. An initial flight test envelope expansion was accomplished so that the pilots could refine clinical PST maneuvers derived from simulation.

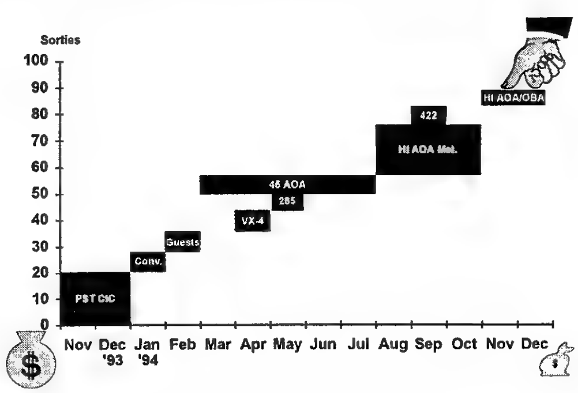


Figure 10: Tactical Utility Flight Testing Events

Once pilots had achieved sufficient proficiency in PST maneuvering, unscripted CIC testing was accomplished in test blocks. These blocks were defined by parametric changes to baseline weapons and PST maneuver limits as well as adversary aircraft capabilities and are shown in Figure 10.

8.1 Tactical Utility Evaluation Events

As already shown in Figure 10, the major X-31A tactical utility evaluation events were PST CIC, conventional CIC, guest pilots and guest adversary aircraft evaluation, as well as parametric changes in AoA limit to 45°, PST entry speed limit to 265 kts, and various missile launch envelopes (high AoA missile only limited to the launch platform's AoA limit and high off-boresight missile launches).

Due to classification issues quantitative results of all TU evaluation phases cannot be presented here (see [5]), some qualitative remarks however can be given.

USAF and USN 'guest' pilots confirmed results demonstrated by X-31A cadre pilots and demonstrated that combat-ready fliers could use PST effectively in CIC without extensive training.

Pilots from VX-4 (the USN West coast operational evaluation squadron based at Point Mugu NAS, CA) with F-14B/D and F/A-18C aircraft and pilots of the 422 TES (the USAF operational test and evaluation squadron from Nellis AFB, NV) with F-15C and Block 52 F-16C flew against the X-31A and yielded considerable insight into both the value and limitations of PST capabilities in CIC. Thus they helped to isolate critical EFM design parameters.

Limiting the X-31A to 45° AoA isolated effects of velocity-vector roll capabilities from high AoA capabilities so that relative contributions of each to CIC effectiveness could be studied. In general, the X-31A derived significant combat advantage by using thrust vectoring to retain considerable lateral and directional control at PST AoA. Velocity vector roll rate and high AoA capabilities are complimentary. Since technical requirements and associated costs are the same for 45° and 70° PST maneuvering, and the benefits of 70° AoA capabilities are higher, no sensible design trade exists on AoA limit beyond stall.

Advanced missile capabilities were simulated by permitting missile launches at high AoA and high off-boresight. The helmet-mounted display used for some of these tests enhanced pilot awareness of weapon envelopes, which increased CIC effectiveness.

8.2 Conventional versus PST CIC

As some data of conventional CIC of the X-31A versus an X-31A with full PST capabilities is unclassified it enables a comparison here.

Figure 11 depicts the tremendous advantage of the X-31A using PST. The X-31A exploiting its full PST capabilities is significantly superior in CIC against an F/A-18 degraded to resemble the X-31A in conventional performance. That this goal of equal conventional performance wasn't quite achieved is visible in the left-hand side of Figure 11. The X-31A won only 15% while the degraded F/A-18 scored 46% of all 28 engagements thus no perfect equality was established.

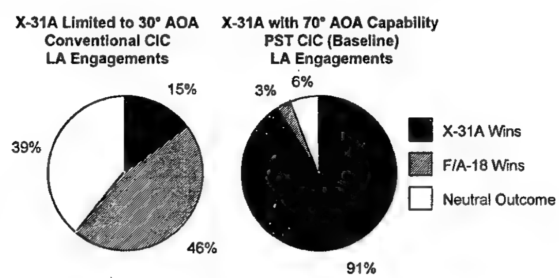


Figure 11: Conventional vs. 70° AoA CIC

However looking at the right-hand side of Figure 11 the X-31A using its unique PST capabilities won 91% of all engagements from neutral, line-abreast starting conditions. This is an improvement in combat outcome by more than a factor of 6 as compared to the case of the X-31A restricted to conventional flight, i.e. limited to 30° AoA.

Using Equations (4) and (5) and flight test data primary measures of effectiveness could be calculated (Figure 12):

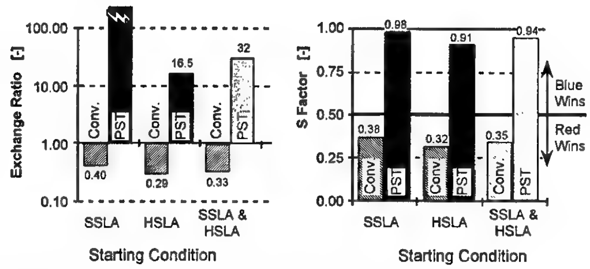


Figure 12: Conventional vs. 70° AoA CIC

8.3 Weapons Employment Geometry

Evaluation of the weapons employment geometry is depicted in the following two figures. The gun shot geometry of the X-31A in poststall CIC is shown in Figure 13. The preferred gun-tracking position is in beam aspect (looking into the side of the adversary which is symbolized by the cross in the center of the polar plot of Figure 13). A high-AoA missile threat drives the gun ranges inside 2000 ft. The X-31A's opponent is forced into the PST 'killing zone'.

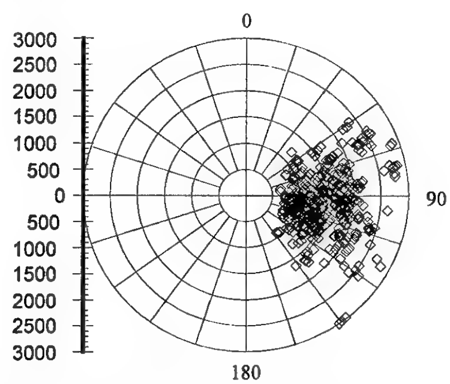


Figure 13: Gun Shot Geometry (Poststall CIC)

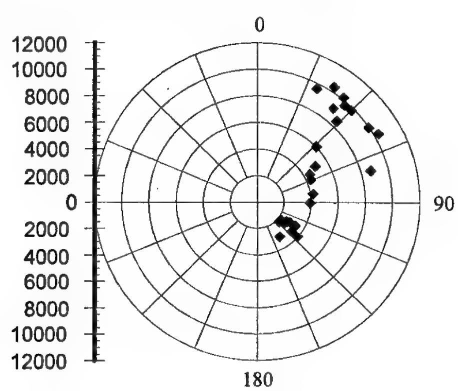


Figure 14: Missile Shot Geometry (High-AoA Missile CIC)

Looking at the missile shot geometry in Figure 14 of an X-31A using PST and equipped with a generic high-AoA missile, one can detect forward quarter missile hits possible since the X-31A can shoot before the opponent breaks the minimum range boundary.

The X-31A can choose to allow the fight to expand and employ the missile, or press for a gun kill as described before.

8.4 Post Stall Maneuvers

The flight regime beyond stall houses several unique types of maneuvers of which two will be described here. Not being limited to the maximum aerodynamic lift during heading changes as in conventional flight (see Equation 8) PST maneuvers are characterized by extremely small turn radii.

Substituting the load factor in Equation (3) by

$$n_z = \frac{L}{mg} \tag{7}$$

yields with the lift coefficient C_L an expression for the minimum turn radius r_{min}:

$$r_{\min} = \frac{V^2}{g} \cdot \frac{1}{\sqrt{\left(\frac{C_{L_{\max}} \frac{\rho}{2} V^2 S}{mg} \right)^2 - 1}} \tag{8}$$

A considerable contribution by the thrust vector to balance the weight, i.e. an increase of the denominator, allows for smaller turn radii.

The clinical 'Herbst Maneuver' and a maneuver resembling a 'funnel' or a 'fire pole' belong to the typical PST maneuvers.

8.4.1 'Herbst Maneuver'

The 'Herbst Maneuver' is a very tight 180° heading change [3]. It is depicted in Figure 15.

Figure 15: Herbst Maneuver

The 'Herbst Maneuver' is characterized by the following phases: The X-31A enters the maneuver at high speed. A rapid deceleration while increasing angle of attack exceeds the conventional aerodynamics limit (stall) reaching an angle of attack of 70°. In this PST flight condition the X-31A performs a velocity vector roll, i.e. a coordinated body axis roll and yaw maneuver. With this 'coning' motion a new flight direction, i.e. a heading change, is achieved. Unloading and decreasing the angle of attack the X-31A terminates the 'Herbst Maneuver' in an accelerating fashion.

8.4.2 'Fire Pole'

A PST maneuver with an even greater impact on tactical utility is shown in Figure 16.

Closing in onto the adversary both aircraft try to establish a gun tracking solution. While the adversary's turn radius (refer Equation 8) is limited by its maximum possible load factor, i.e. maximum lift, the X-31A can exploit its PST capabilities. The adversary aircraft (solid aircraft in Figure 16) bleeds off speed to achieve smaller turn radii and to establish a gun tracking solution. Having reached its minimum turn radius, the adversary aircraft is restrained to circling

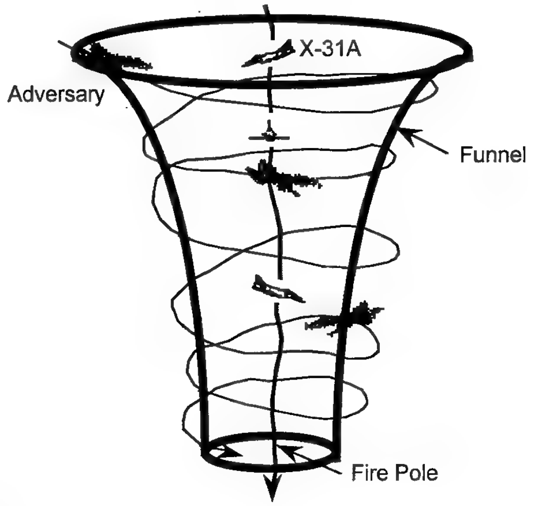


Figure 16: 'Fire Pole'

at this turn radius. Thus its flight path describes the surface of a 'funnel' with a cylindrical lower part. The X-31A however slides down a 'fire pole'. With its extremely tight turn radii and its aircraft reference line decoupled from its flight path, the X-31A can permanently threaten the adversary. The X-31A's motion along is referred to as 'Helicopter Gun Attack' maneuver since the X-31A can turn its nose and thus its gun aiming line like a helicopter.

9. CONCLUSIONS

As no aircraft before the X-31A has demonstrated post stall capabilities up to 70° angle of attack. The X-31A using post stall technologies including a thrust vectoring system was significantly superior in CIC to various state of the art fighter aircraft. Improvement in CIC effectiveness was not only a mere few percent but changed by almost an order of magnitude.

Even though the X-31A was a low cost demonstrator and thus aerodynamically anything but optimized, it was perfectly suitable to evaluate the tactical utility of aircraft with post stall capabilities. The delta-canard configured single engine X-31A has flown a total of 580 flight during its flight test program. The joint efforts of the International Test Organization as it united various international partners from Germany and the USA including the two main industry contractors Daimler-Benz Aerospace AG and Rockwell International enabled a timely and cost-efficient experimental program.

The X-31A aircraft with its thrust vector control in both pitch and yaw axes in conjunction with a highly sophisticated flight control system experienced a maneuverability and agility never seen before. The technical feasibility and tactical utility of post stall capabilities have impressively been proven as described qualitatively and quantitatively in this paper. Maxims of aerial combat like '*Speed is Life*' have been rendered obsolete as with the X-31A and its capabilities came the dawn of a new area of CIC tactics. Various maneuvers unique to the post stall arena like the 'Herbst Maneuver', an extremely tight heading change, and maneuvers with phases of decoupled fuselage reference line from the flight path like in a 'Helicopter Gun Attack' have been demonstrated by the X-31A and are presented here.

Given sufficient thrust-to-weight ratio, thrust vectoring provides not only post stall maneuvering capabilities through the additional control power by the thrust vector but also superior conventional performance for smaller turn radii, higher turn rates, higher pitch rates, etc. as described analytically here. This enhanced fighter maneuverability in turn assured superior weapon pointing and velocity vector roll capabilities at slow speed and high angle of attack, as well as departure resistance for carefree handling. All are essentials for success in CIC. Proper and timely employment of post stall maneuvering in CIC significantly improves the combat effectiveness not only in offensive and neutral starting conditions but also in defensive maneuvering.

Various tactical utility flight testing phases unveiled several sensitivity parameters to CIC effectiveness (see [5] for details). Qualitatively it can be stated that thrust vector control and supporting enhanced fighter maneuverability technologies provide tremendous airframe growth potential and might even be suitable not only for future fighter aircraft design but also for mission-enhancement upgrades to current fighters.

Besides its almost 400 CIC engagements guaranteeing statistical significance the X-31A aircraft have set several records for flight test efficiency and productivity. The benefits of thrust vectoring and enhanced fighter maneuverability were clearly and convincingly demonstrated, not only by the tactical utility evaluation but also by X-31A flight test initiatives. These include the X-31 Quasi-Tailless (QT) demonstrations [17] and the Low Altitude PST Envelope Expansion conducted in preparation for the Paris Air Show in 1995. The attendant risk of incorporating enhanced fighter maneuverability technologies has been reduced significantly.

10. ACKNOWLEDGMENT

The authors would like to express their deep appreciation for all the support granted to them during the X-31A TU flight test campaigns. Without all eight major partners from US and German government agencies and US and German contractors (including various subcontractors like Honeywell, GEC Marconi, the German Aerospace Research Establishment DLR, and WTD-61 to name a few) united in the International Test Organization (ITO) the X-31 program couldn't have been as successful as it was.

The players in the X-31 program under a Memorandum of Agreement and an Associate Contractor Agreement were ARPA and FMOD, the German Ministry of Defense, as well as the US Air Force and US Navy, the German Luftwaffe, NASA, and the two industry partners Rockwell International and Daimler-Benz Aerospace AG. All their logos are included in the ITO logo as shown in the Figure 17.

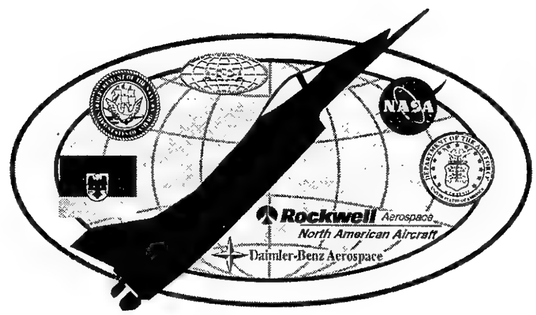


Figure 17: ITO Logo

11. REFERENCES

[1] Robinson, M.R. and Herbst, W.B.: *The X-31A and Advanced Highly Maneuverable Aircraft.* 17th ICAS Congress, Stockholm, Sweden, 1990, Proceedings Vol. I, pp. LV - LXIV

[2] Francis, M.S.: *X-31: An International Success Story.* Aerospace America, Feb. 1995, pp. 22 - 27 & 32

[3] Herbst, W.: *Advancements in Future Fighter Aircraft.* AGARD CP 147 Aircraft Design Integration and Optimization Vol. I, 1973, pp. 25.1 - 25.7

[4] Skow, A.M.: *Agility as a Contribution to Design Balance.* AIAA Paper 90-1305, AIAA/SFTE/DGLR/SETP 5th Biannual Flight Test Conference, Ontario, CA, May 22 - 24, 1990

[5] Eubanks, D. A.; Friehmelt, H.; Gütter, R.; Haiplik, R.; Kim, Q.; and Lee, B. L.: *X-31 Tactical Utility - Final Report.* Dasa / Rockwell / USAF / ITO Report, ITO 95-03, NASA Dryden, 1995

[6] Eubanks, D.; Gütter, R.; and Lee, B.: *X-31 CIC Flight Test Results.* 4-PWR SM TG Workshop on Full Envelope Agility, Eglin AFB, Mar 28 - 30, 1995, pp. 31 - 47

[7] Haiplik, R. and Gütter, R.: *Taktische Flugerprobung X-31.* DGLR-Paper 94-C4-055, DGLR Jahrestagung, Erlangen, 1994, pp. 423 - 428

[8] Friehmelt, H.; Weiß, S.; Rohlf, D.; and Plaetschke, E.: *Using Single Surface Excitation for X-31 System Identification at High AoA.* Society of Flight Test Engineers (SFTE), 26th Annual Symposium, Berlin, June 19 - 23, 1995

[9] Georg, H.-U.: *Aerodynamic Development and Effectiveness Evaluation of the X-31 Thrust Vectoring System.* 4th High Alpha Conference, NASA Dryden, July 12 - 14, 1994, NASA CP-10143, Vol. 2

[10] Beh, H. and Hofinger, G.: *Control Law Design of the Experimental Aircraft X-31A.* 19th Congress of the International Council of the Aeronautical Sciences, AIAA, Paper ICAS 94-7.2.1, Anaheim, CA, Sep 18 - 23, 1994

[11] Bartoldus, K.H.: *Helmet Mounted Visual Audio Display (HMVAD) Symbology Evaluation during X-31 Tactical Utility Flight Test.* Deutsche Aerospace, Dasa/LME11/X-31/TN/85, Ottobrunn, May 1994

[12] Huber H.; and Galleithner, H.: *Control Laws / Flying Qualities and Flight Test Results.* High-Angle-of-Attack Projects and Technology Conference, NASA Dryden Flight Research Center, 21. - 23. April 1992, NASA-CP-3137, Vol. 1, pp. 171-188

[13] Huber, P. and Schellenger, H.: *X-31 Flugeigenschaften im Hochanstellwinkelbereich.* DGLR Jahrestagung, Paper 94-C4-056, Erlangen, Oct 4 - 7, 1994, pp. 429 - 436

[14] Reif, A.: *An Agility Metric Structure for Operational Agility.* AGARD Flight Mechanics Panel Symposium, Annapolis, MD, Oct 18 - 21, 1993, AGARD CP-548, pp. 24.1 - 24.15

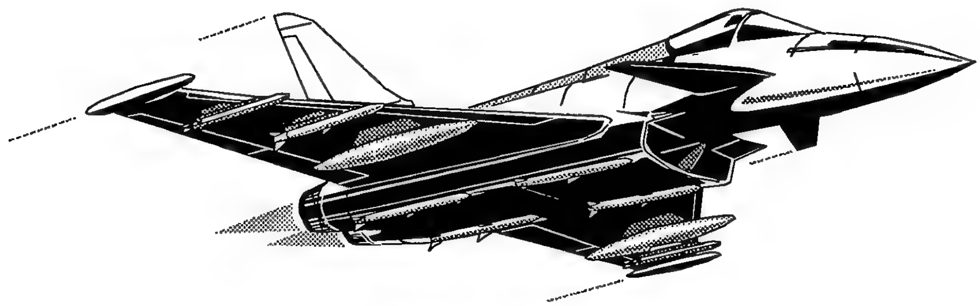
[15] Przemieniecki, J.S.: *Mathematical Methods in Defense Analyses, 2nd Edition.* AIAA Education Series, ISBN 1-56347-092-6, 1994

[16] Haiplik, R.; Polis, R.; and Wimbersky, G.: *X-31 Tactical Utility Simulation Pinball 2.* Deutsche Aerospace AG, Dasa/LME12/R/74, Ottobrunn, September 1993

[17] Huber, P.: *Control Law Design for Tailless Configurations and In-Flight Simulation Using the X-31 Aircraft.* AIAA Guidance, Navigation, and Control Conference, Paper AIAA 95-3199-CP, Baltimore, MD, 6. - 10. Aug. 1995, pp. 247 - 257

THE EUROPEAN FIGHTER AIRCRAFT EF2000 FLIGHT TEST PROGRAMME OVERVIEW AND MANAGEMENT CONCEPT

Michael Herr and Paul Butcher
Eurofighter Jagdflugzeug GmbH
Am Soeldnermoos 17
D-85399 Hallbergmoos, Germany



SUMMARY

The Eurofighter 2000 (EF2000) Flight Test programme began with first flight in 1994. The aircraft will enter service at the beginning of the next century.
In addition to the challenge of basic certification of the airframe with many different Air-to-Air and Air-to-Ground stores configurations, Eurofighter Partner Companies are also conducting testing to fully integrate the new developed Radar (ECR90) and Engine (EJ200). This paper constitutes a description of the EUROFIGHTER Weapon System, the flight test programme management, an overview of the test programme plan and progress to date and discussion of unique challenges during testing.

Up to now the EF2000 flight test programme has proceeded as planned and in-service certification should occur on schedule. The achievements reached so far can be attributed to a well designed and built aircraft, a comprehensive test plan, a very reliable data system, and the personal efforts of thousands of people in four different countries.

1. INTRODUCTION

The EF2000 Development is a four nation programme (Germany, Italy, Spain, United Kingdom) - as shown in Figure 1 - in response to the European Airstaff Requirement issued December 1985 for an Air Superiority Fighter with a Secondary Role Capability for Ground Attack.

The prime contractor for the development is the Eurofighter Jagdflugzeug GmbH which manages the project activities of the four partner companies Alenia (ALN), British Aerospace (BAe), CASA and Daimler- Benz Aerospace (Dasa).
The Aircraft is a single seat, twin engine, aerodynamically unstable delta-canard design embodying latest technology in structures, systems, engine and avionics optimized for the air-to-air role. Design emphasis is placed also on operability, reliability, maintainability and testability as well as low mass and low radar signature. The radar is optimized for air-to-air with reliable operation in a high density ECM environment.

The Flight Test Programme consists of 7 Development Aircraft plus 5 Instrumented Production Aircraft shared between the partner

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

companies to develop the design through initial operational certification to the final standard.
Advanced Flight Test Instrumentation and Analysis Methods will be used for cost effective and economic flight testing.

2. EF2000 PROGRAMME BACKGROUND

Full-scale development of the Eurofighter 2000, formerly called European Fighter Aircraft, began in 1988 by the United Kingdom, Germany, Italy and Spain. A consortium to develop the aircraft was formed with the shares of the industrial partners - British Aerospace and Daimler-Benz Aerospace at 33%, Alenia at 21% and CASA at 13% - in proportion to each country's expected requirements for the aircraft. Eurojet, the company responsible for developing the engine, reflects the same breakdown.

Similar workshare principles are arranged for production where e.g. Dasa build the centre fuselage, British Aerospace the front fuselage, (incl. cockpit, and canard foreplanes) and the vertical tail. CASA build the right wing whereas the left wing is built by Alenia with the rear fuselage shared by BAe and Alenia.

A total of more than 600 aircraft are to be ordered by the four air forces, with close and beyond visual range (BVR) air-to-air combat as their primary role. A life-time of 6000 flight hours (or 25 years, whichever comes first) is envisaged. The aircraft basic empty mass is defined to be around 10 t. A high thrust to weight ratio will be achieved with two engines of the 90 kN thrust class.

The basic design features are as follows:

o Delta canard configuration, aerodynamically unstable platform;

o quadruplex digital fly-by-wire flight control system;

o Chin intake;

o Use of advanced materials;

o Single-seat configuration;

o advanced mission avionics;

o state of the art cockpit design.

The two-seat version is to include the same basic dimensions for commonality across airframe and systems.
As regards industrial aspects, the worksharing principles are:

o All key technology aspects to be equally shared by the partners;

o Duplication to be avoided;

o Final assembly lines in each nation;

o Flight testing to be carried out at each company.

3. EF2000 TECHNICAL LAYOUT AND ASSOCIATED FLIGHT TEST ACTIVITIES

3.1 Aerodynamic Concept and Flight Control System (FCS)

The Delta-Canard Configuration
The delta-canard configuration proved to be superior to competing designs with respect to point and mission performance. Detailed design studies and trade-offs were carried out to achieve on overall balanced design within the stringent constraints. The main advantages offered by the delta wing configuration, when compared to trapezoidal planform were in the sub-sonic regime, include higher maximum lift due to the large wing area, and in the supersonic flight regime, reduced aerodynamic centre shift resulting in lower trim drag and better sustained turn rates with higher specific excess power.
The delta wing configuration also provides low weight per unit area, high volumetric efficiency (fuel content) and a long moment arm for effective flap, trim and control power.

All-Moving Foreplane
The longitudinal instability of the airplane is achieved by the all-movable foreplane (canard). With the correct and favourable foreplane-wing interaction, maximum lift is increased while lift-dependent drag at high angles of attack is reduced. The foreplane is used to trim the aircraft for maximum performance.

The aircraft is inherently unstable in the longitudinal axis in the subsonic regime, and becomes longitudinally stable and directionally unstable in the supersonic area. The modern digital flight control system provides artificial stabilisation.

As an overall result, the EF2000 concept offers a significantly better supersonic turning performance, when compared with a conventional design with trapezoidal wing and aft tail.

Flight Control System (FCS)
The flight control system is a full-time, full-authority quadruplex digital fly-by-wire system. It provides excellent handling qualities and carefree manoeuvring in all stores configurations. The pilot can use the stick, rudder and throttles in any combination in the knowledge that maximum manoeuvre performance will be provided without risk of loss of control, overstress or engine surge. The variation of fuel state and the firing or jettison of weapons are automatically compensated. Voice warnings are issued if the pilot allows the airspeed to drop below safe values.

The stick is centrally mounted, with small displacements and light stick forces. In pitch, the pilot perceives neutral static stability except for landing where artificial positive static stability is provided. In manoeuvre, stick force per g is constant in the g-limited envelope. The roll response is controlled to respect both loading and handling limitations. Above 2g, wind axis rolls are commanded for minimum sideslip. The rudder pedal is used only to kick-off drift on landing.

Flight Test Aspects
The primary objective of evaluating the general flying qualities of the aircraft is to provide a "carefree" service clearance (i.e. no loss of control or overstressing) for operational agile manoeuvring in all store configurations.

Beside the "classic" assessment of system characteristics (A/C + FCS + pilot) in closed loop manoeuvres (e.g. air to air tracking, in-flight refuelling, landing, aerobatics) special emphasis is laid on the "carefree" part. This will be done by evaluating the handling qualities at maximum AOAs, g's, roll rates and with operational representative manoeuvres to check the capability of the FCS to protect the A/C from loss of control due to excessive AOA, sideslip or roll rate.

Until the carefree protection is proven the test aircraft will be equipped with special safety devices, including anti-spin parachute and emergency power supplies (EPS). The Flight Control System (FCS) will feature a recovery mode to prevent undesirable control movements should a spin occur.

The FCS Software (S/W) in addition to the S/Ws for Avionic and Utility systems are fed "stepwise" into the Flight Test Programme, i.e. the provided S/W for a certain programme phase should provide the functionality to satisfy programme objectives. The advantages compared to a direct approach are mainly seen in the facts that the overall technical risk can be managed easier and intermediate steps can be reached with less risk.

3.2 Structural Concept

The concept to achieve minimum weight is to optimise loads, extensively use advanced materials and maximise structural integration. This leads to a saving of approximately 25% compared to conventional techniques. For the optimised loads concept the flight control system provides precise control of normal acceleration and roll parameters to control structural loads. This allows a reduced ultimate factor for stressing calculations, further reducing weight. Advanced materials (carbon fibre reinforced composite, improved aluminium alloys and aluminium lithium alloys) are extensively used throughout the A/C. More than 70% of the wetted surface and about 40% of the basic structure are made from Carbon Fibre Composite (CFC).

Flight Test Aspects
Related to the A/C structure the main objectives of the flight test programme are on Flutter, Structural Health Monitoring, validation of design loads, structural temperatures and vibrations/ acoustic noise.

The EF2000 requires a "classical" flutter evaluation but the configuration places special requirements on the flight test technique. In particular, the foreplane is a critical surface for flutter, however its sensitivity to mass precludes the use of traditional excitation by pyrotechnic devices ("bonkers"). Fitting a "bonker" pack for excitation would invalidate the flight test results. Therefore the FCS is used as the excitation method for flutter flight trials. A special flight test facility called the FBI ("frequency and bias input") injects frequency sweeps or impulse signals into the control surfaces, tailored according to the predicted characteristics of the surface under test.

Although mandated by the foreplane characteristics, the FBI is used for excitation of all surfaces. Therefore, since there are no excitation system consumables, the number of tests achievable per flight is limited only by the aircraft's fuel endurance.

The FBI is also used to excite the A/C for measurement of structural coupling and Air Data System (ADS) effects in flight allowing the FCS structural filters to be optimised for the wide range of weapon configurations.

The EF2000 will be equipped by a Structural Health Monitoring (SHM) system which utilises airframe response parameters to provide an on-board record of cumulative fatigue damage occurred at various airframe locations. Parametric and strain gauge data will be recorded by Flight Test in all phases of flight as a "ride along" exercise to develop and verify the operation of the SHM.

A very special FTI equipment is used for measurement of A/C loads. One development A/C will be fitted with a matrix of piezo-resistive pressure transducers distributed all over the external skin of wing, foreplane, fin and fuselage. By measuring the static surface pressure with this so called "pressure plotting survey" the aerodynamic loads can then be calculated via pressure integration.

3.3 Engine

The EJ200 engine is tailored specifically to match EF2000's mission requirements. In particular it offers a combination of very high thrust - around 90 kN in full reheat and 60 kN in full dry power - and low fuel consumption and carefree handling. As with the airframe, great emphasis is put on reliability and maintainability, low cost ownership, and growth potential.

The EJ200 is a two-spool turbofan with modular construction for ease of maintenance and support. The broad blades of its wide-chord fan are light and aerodynamically efficient as well as possessing a high level of resistance for foreign object damage. Both the high and low pressure compressors are driven by single stage advanced air-cooled turbines, featuring the latest single crystal blade technology. Low smoke and emission characteristics have been designed for the main, annular combustor which incorporates air spray fuel injectors. The reheat system features radial burners and a hydraulically operated convergent/ divergent nozzle. All accessories, including the full authority digital engine control unit (DECU), are self-contained and engine mounted. An auxiliary gearbox on the underside of the engine provides drive for the accessories.

Flight Test Aspects

Before the first flight of an EJ200, about 3000 hours of Ground Testing with 11 Development Engines was performed. This large amount of test experience - compared to former programmes, e.g. RB199 on Tornado - allowed a very rapid progress in flight testing the engine. Additionally, the EJ200 proved its very rugged design and extraordinary reliability at this early stage in the flight test programme. For the flight development programme about 30 engines in three different standards will be delivered.

The anticipated trials to verify and validate the engine integration with the EF2000 weapon system are, in general, straight forward, i.e. engine handling, vibration, oil system etc..

Nevertheless, a special EJ200 feature should be highlighted. The engine control and Health Monitoring System are fully integrated into the architecture of the A/C digital inter-system communication. The advantages for that lies in mass reduction, quicker response and lower deadbands compared to former hardwired links like used on Tornado. Also the autopilot demands are routed directly to the Digital Engine Control Unit (DECU) from the Flight Control System (FCS) avoiding any mechanical interface in the loop.

In flight test, where different S/W standards will be tested during certain programme phases, the compatibility between interfaces (e.g. FCS/ DECU) must therefore be assured and validated.

Beside engine performance tests to evaluate the installation losses also thrust-in-flight measurements will be performed. Based on a theoretical model - verified by Sea Level Test Bench and Altitude Test Facility Calibration - in-flight thrust can be calculated for all flight conditions in the flight envelope by measuring certain engine parameters. This is of significant importance for validation of A/C drag and performance.

To verify the windmill and assisted relight envelope DA3 will be equipped during the time of relight testing with an Auxiliary Power Unit (APU) operative in flight. The APU is used as a flight safety device only in case a double-engine-flameout occurs to provide an adequate and engine independent source of hydraulic power. It also can unload the engine from mechanical load thus increasing the relight capability in windmilling conditions.

3.4 Utility Control System (UCS) and General Systems

General
To fulfil the requirement of single crew operation design activities concentrated on low workload, high performance capability, high availability rates and good maintainability. The various systems have been incorporated within a fully integrated architecture.

The Utilities Control System (UCS) controls all general systems with the exception of the Flight Control System (FCS). It provides continuous controlling, monitoring and fault finding of all these sub-systems. The utilities control system comprises essentially 6 computers and a Maintenance Data Panel (MDP).

The MDP forms a major contribution to the mission readiness concept of the aircraft. It offers a clear text indication of each LRU-failure diagnosed on board. It shows level status of usable items, allows refuelling and defuelling services and also the initialisation of Build-in Test (BIT) of the systems. A transportable data carrier module is provided for data analysis. If required, further equipment can be connected to the UCS data bus for data evaluation.

Flight Test Aspects
All main systems are tested on ground test rigs prior commencement of flight tests to generate confidence in the system functionality and reach a flight clearance status. Most of system flight tests will be carried out "ride along" in conjunction with Performance (flight envelope), Handling (max g / AOA) and Engine trials (Relight trials).

Beside the general flight test objectives e.g. demonstrate compliance with the design goals and with the requirements of the specification, the following system trials will receive special consideration:

- Environmental Control System (ECS):
Hot/cold weather trials to check satisfactory operation of the system at world wide extreme temperatures.

- Hydraulic Generation System:
The satisfactory performance of the hydraulic system will be demonstrated in simulated flight emergency conditions. Also failures of individual utility systems will be simulated during the flight.

- Fuel System:
To demonstrate the ability of the fuel transfer sequencing to control the aircraft centre of gravity within the specified limits and to demonstrate the correct operation of fuel computers including software for system management, gauging and monitoring function. Emphasis of this testing will be laid on critical flight conditions for the fuel supply, e.g. climbs, dives, negative and zero 'g' and low fuel states.

In-flight refuelling tests to validate fuel system and A/C Handling in a variety of configurations and against different tankers. This ability is essential to the flight test programme with respect to extend sortie length and trials flight time.

- Secondary Power System:
To check the ability to provide sustained hydraulic/electric power and assisted relight capability, during one engine flame out case (cross bleed operation).

- Aircrew Equipment Assembly:
To assess the complementing "g-clothing" (e.g. pressure breathing, full coverage anti-g trousers etc) under extreme g-onset rates and maximum g values, to prevent "G-Loc" Problems.

3.5 Avionic System

Avionics Systems Integration
High mission effectiveness and survivability of EF2000 will be realised through an integrated avionics system comprising seven functional sub-systems - all working together to give the pilot an autonomous ability to assess the tactical air situation and fight the battle. The individual systems are difficult to describe in isolation simply because of the degree with which they are integrated - and it is due to this sharing of information between the sub-systems that the pilot will be presented with a much more comprehensive picture of his air environment than he has previously been used to.

Functional Subsystems
As the whole avionic system is to be operated by a single crew member, an acceptable workload has to be assured by automating the system functions and moding as far as possible.

The avionic system is an integrated system that can be divided into the following subsystems:

o Armament Control System (ACS)
o Attack and Identification (A & I)
o Communications (COMMS)
o Defensive Aids Sub System (DASS)

o Displays and Controls (D & C)
o Integrated Monitoring and Recording System (IMRS)
o Navigation (NAV)

During the early development phases of the programme, the Customer Operators were involved in agreeing the Man-Machine Interface (MMI) aspects of the cockpit layout, and the associated cockpit moding, as shown in Figure 2. This Customer involvement has since extended to manned-simulation assessments of a representative EF2000 cockpit. Software loads for these assessments have been representative of both the Initial Operational Clearance (IOC) version, and the Full Operational Clearance (FOC) standard of production aircraft. This close co-operation with the Customer has been extremely useful in helping to ensure that the complex interaction between the pilot and the Weapon System is fully optimised to suit the specific needs of the 4 Air Forces involved in the EF2000 programme.

Flight Test Aspects
Some highlights out of the complex, integrated Avionic System trials are e.g.:

- To demonstrate satisfactory operation and performance of the functional subsystems in accordance with the A/C Specification.

- Look at all operationally important areas e.g. attack/weapons/displays/defensive aids systems including jamming scenarios in order to identify any problems.

- To achieve an IFR Clearance and navigation accuracy data at an early stage of the EF2000 flight test programme to ensure efficient progress.

- To test and demonstrate satisfactory data display, handling, pilot interaction and workload ("Man-Machine-Interface").

- To demonstrate system operation and degradation in the case of equipment failures in the primary and reversionary modes.

- The Defensive Aids Sub-System (DASS) will be checked inflight for its capability of suppression management and selection of appropriate counter measures against specific threats.

- The Multi-functional Information Distribution System (MIDS) will be evaluated under certain threat scenarios to check the secure exchange of tactical information with users on a common network.

- The overall integration aspect of the Avionic System layout is extremely evident in the requirement for sensor fusing of target data derived from several different sources, namely Radar, MIDS, FLIR, DASS and Identification Friend / Foe (IFF). The objective of flight trials will be to evaluate the capability to provide the pilot with an autonomous capability to assess the air situation and fight the air battle. This should be provided by association, correlation and fusion of data from the on-board sensors and from the off-board data received via MIDS.

- The Weapon Aiming System will be checked for providing of adequate data and aircrew operating guidance for use of Air-to-air and Air-to-ground weapons.

3.6 Radar

The ECR 90 radar is being developed by Euroradar, a consortium led by GEC Marconi of UK, with ENOSA of Spain, FIAR of Italy, and Dasa of Germany. It is an advanced pulse-doppler system with high technology features throughout, particularly within the transmitter, antenna, and signal processor. Much of the technology has been derived from the highly successful Blue Vixen radar.
DA5 will be the first of four of the development aircraft to be fitted with the ECR 90 radar.

Flight Test Aspects
Specific objectives with respect to programme milestones planned to be reached in a stepwise approach are:

- Clearing the Air-to-Air Radar modes in manoeuvring flight within the carefree handling envelope, versus manoeuvring fighter aircraft in a non Electronic Counter Measures (ECM) environment.

- Clearing the unrestricted operation in all Air-to-Air Radar modes in an agreed ECM environment

- Clearing Air-to-Surface Radar Modes.

Beside of testing the Radar on-board of EF2000 prototypes, the Radar manufacturers' "Hack" aircraft (BAC1-11) is available to support EF2000 Flight Trials for specific investigations at Radar sub-system level, in addition to rig testing.

Testing of the EF2000 Radar will be closely interwoven with Attack and Identification System proving, Weapon (e.g. AMRAAM, Gun) and Navigation system trials.

Assessment of Air-to-Air / Air-to-Surface Radar performance will require the provision of airborne/ground targets of defined Radar Cross Section (RCS) with operational capability in specified envelopes and incorporating the facility to simulate a variety of hostile ECM techniques.

4. MANAGEMENT ASPECTS

4.1 Flight Test Programme Construction

The flight test programme is required to be shared between the 4 participating partners. The worksharing was defined initially through the number of aircraft allocated to each Flight Test Centre. Then the task allocation was defined taking into account the known expertise of the partners, while ensuring that the overall programme progresses consistently on a "broad front".

This led to a programme comprising 7 Development Aircraft (DA) and 5 Instrumented Production Aircraft (IPA), together performing more than 4000 flights - as shown in Figure 3. The allocation to partners is:

ALN	2 DAs	(DA3 + DA7)	and 1 IPA
BAe	2 DAs	(DA2 + DA4)	and 2 IPAs
CASA	1 DA	(DA6)	and 1 IPA
Dasa	2 DAs	(DA1 + DA5)	and 1 IPA.

The programme adopted the classical risk reduction measure of allocating every task a backup aircraft as well as a prime aircraft, and every aircraft backup tasks as well as prime tasks. Additionally, the first 2 DAs are fitted initially with the well proven RB199 Tornado engine. The definitive EJ200 engine is fitted to DA3 and the subsequent aircraft, and will be retrofitted to DA1 and DA2 about 3 years after their first flights.

The first 3 Development Aircraft are now flying and the remainder will progressively join the flight test programme during 1996.

The flight test tasks of the aircraft can be summarised as follows:

DA1 will be devoted to handling trials and, after retrofit of EJ200 engines, engine development.

DA2 is the airframe envelope expansion vehicle, and will develop and prove the carefree handling capabilities of the FCS.

DA3 is the lead aircraft for engine development and was the first aircraft to fly with the EJ200 engine. It is also the lead aircraft for stores envelope expansion, stores release and jettison testing and gunfiring trials.

DA4 is a two seater and will be the last Development Aircraft to fly. This is because it is undertaking extensive ground trials ahead of flying, including lightning strike testing, Defensive Aids ground testing and calibration of the structural health monitoring system. Once flying, this aircraft is the prime aircraft for avionics integration and radar development.

DA5 is planned to be the first aircraft to fly with radar installed and radar development will be its prime task, together with avionic and weapon system integration testing.

DA6 will actually be the fourth aircraft and the first twin seater to fly. Its prime tasks will be twin seater handling, performance and envelope expansion, followed by development of avionics and systems with particular emphasis on the twin seater capabilities.

DA7 will primarily carry out performance and weapon system integration testing.
Five aircraft from the first production batch will be fitted with FTI and join the flight test programme as Instrumented Production Aircraft. The tasks of these aircraft will be to provide final verification of the Development Aircraft results, plus continuation of the development of the final standards of weapon system software.

4.2 Flight Test Programme Management

The flight test programme described above is complex and highly integrated with multiple dependencies between aircraft and between the four partners. Each partner company is responsible for operating its own aircraft day-to-day, within the medium and long term programmes established centrally by Eurofighter. This obviously requires careful management and a close working relationship between the four flight test centres. This is achieved through the Flight Test Panel which is formed by the Flight Test Managers of the four partners, plus Eurofighter (Figure 4 refers).

This Panel was established in the earliest days of the project to lay down the principles of the flight test programme, and it continues to manage the active trials and future planning.

The close working relationships and team spirit built up the Flight Test Panel ensure that the flight trials progress as efficiently as possible, and that problems are overcome with the minimum long term impact.

Specialist sub-groups are established to review progress and exchange information at the more detailed level, under the supervision of the Flight Test Panel.

The four National Official Test Centres (OTCs) are integrated into the Contractor's flight test programme to a greater extent than has been seen on earlier programmes in the Eurofighter Partner Nations. The OTCs have wide ranging access to the contractor's flight test data and have established teams of their own engineers at the Contractor's flight test centres. The OTCs have been consulted during the early planning of the contractor's flight testing and have the right to contribute to the detailed planning so that the contractor flying contributes as much as possible to the Official Service Release Recommendations.

Periodically the OTCs will perform Official Previews and Assessments, where the aircraft is operated from the Contractor's base but the testing is specified by the OTCs. The first Official Preview was performed at Manching on DA1 in March/April 1996.

Additionally, Official Aircrew can perform up to 10% of the contractor's trials distributed throughout the programme. The aim is to maximise the involvement of the Officials in the integrated flight test programme, while maintaining the Contractor's responsibility for completing the development programme in a fixed price contract.

The formal interface for flight test matters between the Contractor (EF) and the Customer (NETMA) is the Operational Requirements and Flight Test Group (ORFT). This group is responsible for reviewing progress in the programme, establishing objectives and ensuring that the necessary external support equipment and facilities are provided as necessary.

A series of maturity criteria and major milestones have been established to allow the progress of the overall development programme to be measured, many of which naturally arise from flight testing. Additionally, short term objectives are declared and tracked to allow progress in flight trials to be assessed.

4.3 Advanced Flight Test Techniques - Real Time Analysis (RTA)

All four partners (through their other projects) are well experienced in the use of telemetry / real time monitoring to improve the productivity of flight test sorties. In order to achieve further improvements in overall cost effectiveness for EF2000, all 4 partners have made significant investments to extend this into true real time analysis. This is used to minimise the turnaround time between the execution of the test and the delivery of the fully analysed engineering result. In many cases this turnaround time can be measured in seconds, allowing the most rapid progress of trials. Real Time Analysis also makes a positive contribution to safety in flight trials by allowing a more detailed understanding of the test just completed, and thus a firmer basis for decision making.

Real Time Analysis has been initially applied to the air vehicle testing performed by DA1-3. Specific highlights have been:

o flutter testing on DA2, with fully analysed frequency and damping results produced within seconds of the end of a test run, with trend analysis in comparison with predictions and previous results immediately available

o handling qualities measurements, where pre-flight predictions of manoeuvre response are stored in a database, to be recalled to the screen and compared directly with the flight responses.

o airdata calibration tests, with on-line comparison of the measured coefficients with the allowable tolerances

o loads estimation, with on-line modelling of loads from flight mechanics parameters and comparison with allowable boundaries - with an alarm if the allowable boundary is exceeded

As the later aircraft join the flight test programme, new real time analysis techniques have been developed for avionic and weapons system trials.

These include:

o real time datalinks from remote instrumented ranges for instantaneous comparison between reference data and aircraft measurements

o the exploitation of differential GPS to allow "ranges" to be established in the local areas of the flight test centres to avoid dependence on radar ranges

o sortie management displays including multiplexed video telemetry of the cockpit head up and head down displays, aircraft and target position displays for situational awareness and aircraft sensor coverage representations

o real time sensor performance assessments through real time sensor emulations in comparison with reference data

o auto selection of test timeslices for the database through monitoring of the combination of aircraft data and intercept profile condition monitoring.

5. FLIGHT TEST STATUS

5.1 Current Flight Test Status

The maiden flight of EF2000 Development Aircraft 1 (DA1) took place on 27 March 1994 from Dasa Flight Test Centre at Manching. DA2 followed shortly with its first flight from BAe Flight Test Centre at Warton.

The maiden flight of the third prototype, DA3, followed on 4 June 1995, from Alenia's Flight Test Center at Caselle, near Turin, Italy.

As of 19th August 1996, the three Development Aircraft involved in flight test so far, have accumulated about 200 hours in 225 flights. More development aircraft are scheduled to be flying within the next few weeks. DA6, the first two-seat Eurofighter 2000 and the first built by CASA of Spain, is now undergoing ground engine tests and is slated to make its maiden flight end of August.

DA1 resumed flight test recently with the latest control system upgrade. With this "2A standard" further expansion of the envelope, e.g. to high angle of attack will be possible. It will also allow "carefree handling" with a "clean" aircraft. A "2B standard" is to be ready by next year, which will allow for carefree handling with weapon stores. It will also introduce the autopilot modes.

The flight envelope opened so far comprises about 90% of the specified speed and Mach values, 70% of altitude and 70% of the AOA/g envelope - as shown in Figure 5. The engine EJ200 behaviour was explored up to supersonic speeds and about 70% of the maximum operational altitude throughout the thrust range.

The first pair of flight EJ200 engines were life expired after completing approximately 118 hours running time each. Their serviceability was exceptional for this early stage in the flying programme, and they have behaved extremely well in the testing. The engine in-flight testing will get more momentum with DA6 flying, which has the next pair of EJ200 engines fitted. The RB199 engines currently still on DA1 and DA2 will be replaced by EJ200 at beginning of next year.

DA4, 5 and 7 are in the final stages of build in preparation for their first flights later this year. Each of these aircraft brings new features to flight testing eg radar (DA5 and DA4), Navigation System (DA7).

About 14 pilots - inclusive 4 OTC pilots - have assessed the aircraft characteristics. Throughout the explored flight envelope the aircraft was described as easy and pleasant to fly. Many pilots expressed their surprise about the great potential the A/C shows even at this early stage of development.

Of course, the operating experience shows also snags in areas of e.g. equipment development or equipment reliability. But all these problems have been investigated and will be resolved by introducing upgraded versions of Hard- and Software.

5.2 Way Ahead

With 3 prototypes flying, the flight test programme has made a solid start in the air-vehicle assessment. The next step will be the addition of the two-seater aircraft to the programme. This will be followed by the start of the intensive and extensive assessment of the highly complex avionic and weapons systems with the later development aircraft.

The participating governments and companies are now in the midst of negotiating the details of a production investment contract.
A memorandum of understanding is expected to be completed by the end of the year. Actual production investment contracts would then be awarded next year.

The long term aim of the programme is to provide the Customer's Air Forces with a highly capable, operationally credible aircraft on the day of the first delivery into service. The addition of the 5 IPAs from the production off-take will allow the conclusion of the development phase and the clearance of the full operational capability of the aircraft in the shortest possible interval thereafter.

6. CONCLUSIONS

Our experience, we believe, led to an excellent standard of collaboration between the EF2000 Flight Test Centres of four different companies, located in four different countries. It illustrates confidence in the ability of the Eurofighter Partner Companies (EPCs) to meet their design targets within the given programme structure and time schedule, provided interface requirements are adequately defined, harmonised and agreed at an early stage like it is done in Flight Test.

All this is happening successfully because of the spirit of cooperation of the many people involved on four sides.

ILLUSTRATIONS:

Figure 1: EF2000 Manufacturing Locations

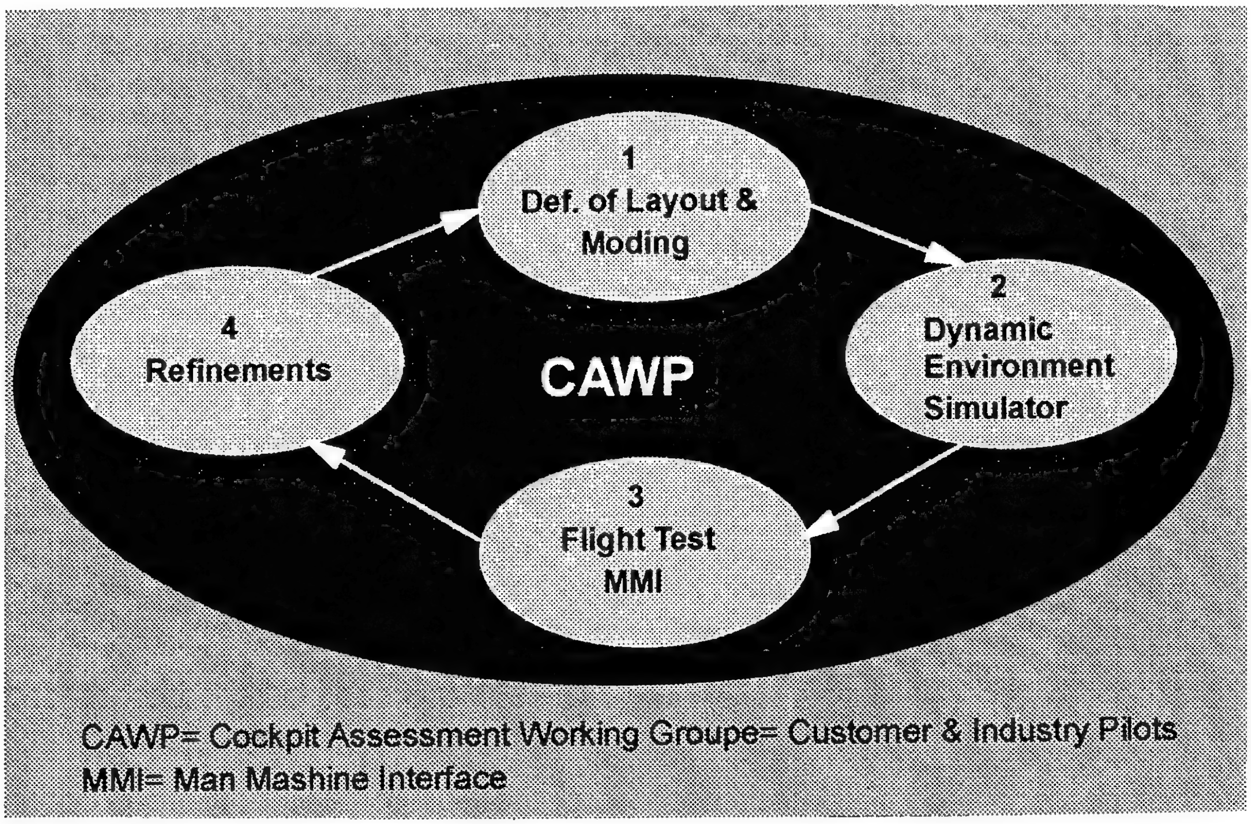


Figure 2: Avionics / Cockpit Development Process

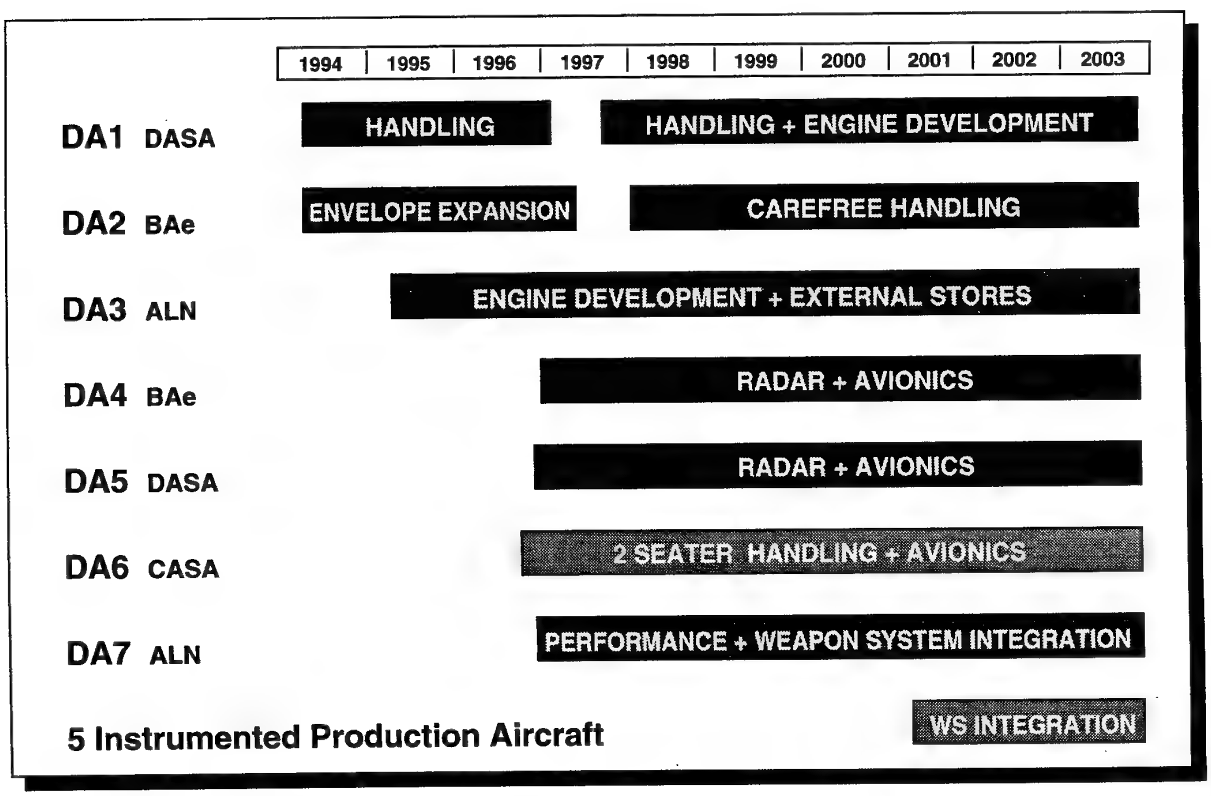


Figure 3: EF2000 Flight Test Programme

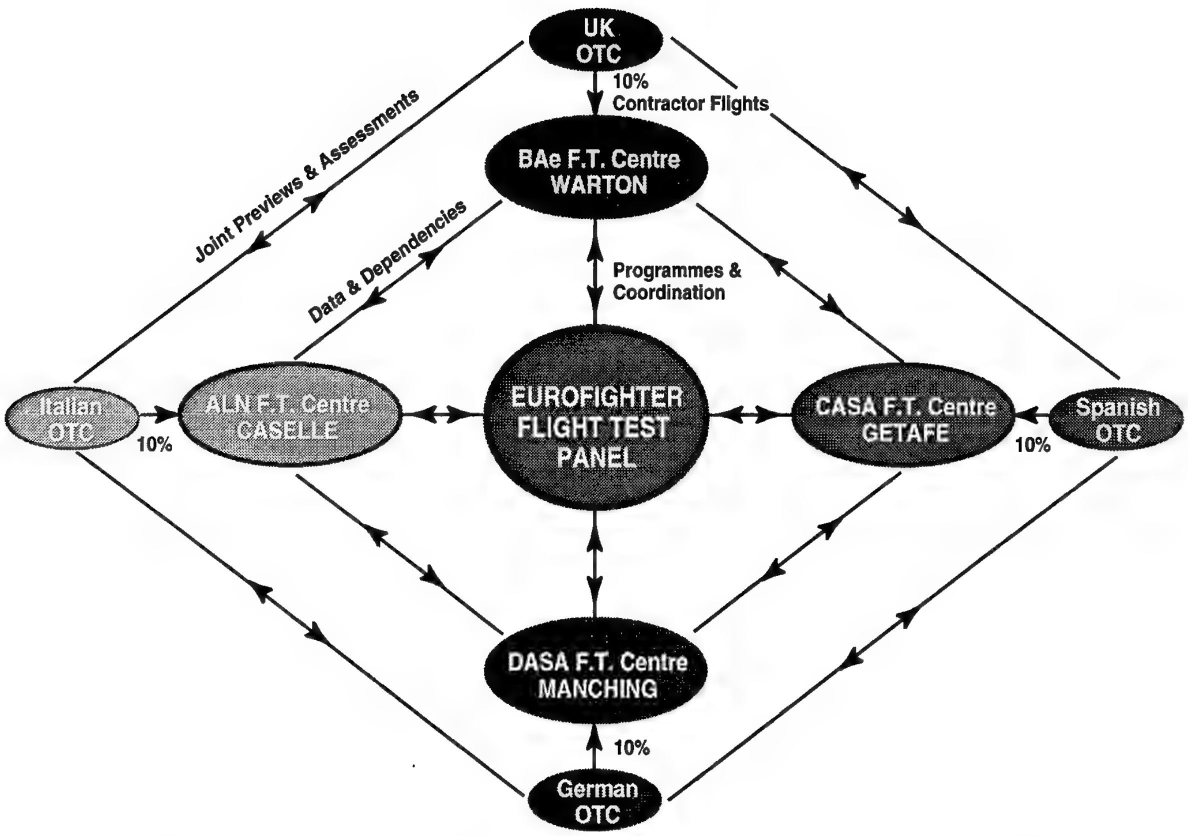
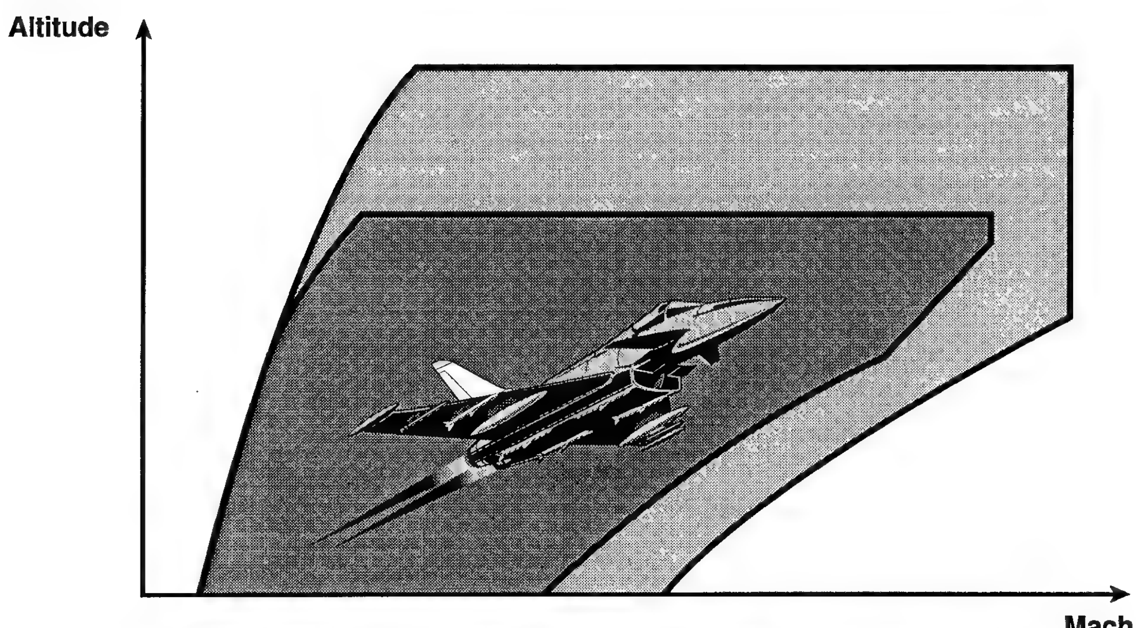


Figure 4: Flight Test Programme Management Structure



Flight envelope covered in appr. 240 flights with:			
AIRCRAFT	DA1 (DASA)	DA2 (BAe)	DA3 (ALN)
ENGINES	RB199	RB199	EJ200

Figure 5: Flight Test Status

THE V-22 OSPREY INTEGRATED TEST TEAM
A PERSPECTIVE ON ORGANIZATIONAL DEVELOPMENT AND TEAMING

Mr. Gery M. VanderVliet, Information Spectrum Incorporated
LTC Robert C. Price, USMC (ret.)
305 Airport Drive, California, Maryland 20619, USA

SUMMARY

In February of 1993 the US Navy's V-22 Osprey Program Management Team established a new way of managing its flight test program. This newly established flight test organization would be a departure from what the Navy Test and Evaluation (T&E) community had been used to, especially for an Acquisition Category One (ACAT I) program. It was that February that the V-22 Osprey Program Manager (PMA) would sign into contract the establishment of the Navy's first Integrated Test Team (ITT).

The V-22 ITT, following in the path of the Air Force Combined Test Force (CTF) concept, would encounter and overcome many challenges. Soon after the V-22 ITT would be established, the Navy's F-18E/F program would follow suit with its own ITT, validating the worthiness of such an organizational concept.

This paper discusses the conception, development, benefits, challenges, and lessons learned associated with the setup and operation of the V-22 Osprey ITT. This paper is written as a perspective from government ITT management only.

1 THE PAST MODEL OF GOVERNMENT DEVELOPMENTAL TESTING

Prior to the establishment of Integrated Test Teams government and contractor flight test organizations conducted separate developmental flight tests. These tests were different in that the contractor would focus on developing the aircraft's flight envelope in accordance with the contracted specification, while the government's efforts concentrated on both mission relation and an independent assessment of specification compliance. Typically, government testers had the attitude that it was their responsibility to find all the problems and deficiencies that the prime contractor either misunderstandingly designed into the aircraft, or, that they were trying to hide.

2 HISTORY OF THE COMBINED TEST FORCE (CTF) AND INTEGRATED TEST TEAM (ITT) CONCEPT

The combined (or integrated) test force (or team) concept was pioneered in the United States by the USAF. Combined teaming is nothing new to industry, in fact, the foundation of the CTF (and ITT) organizational development was the setup of integrated product teams (IPT), a teaming concept first successfully implemented by industry. In retrospect, we can find numerous industry case studies that demonstrate the value of integrating as many developmental functions as possible through effective team management to optimize the efficiency and quality of systems development.

The USAF test community, much like the Navy, went through a series of changing test philosophies associated with their acquisition policy. The most familiar is category testing, wherein first the prime contractor conducts developmental tests, then the service performs developmental test and evaluation (DT&E), and lastly the service performs operational test and evaluation (OT&E). This method is redundant, and even worse, creates a situation were DT and OT deficiencies can not be effectively or efficiently corrected without excessive and postmature cost or schedule impact. There simply had to be a better a way, and in 1972 the Air Force combined the contractor and government DT phases, leaving the OT phase separate. This first ACAT I program to work under a combined test arrangement was the F-16 acquisition program. The Air Force called this setup a Combined Test Force (CTF) established primarily at the Air Force Flight Test Center (AFFTC) Edwards AFB, California.

The US Navy was not so quick to change. It was the changing environment of budget cutbacks and civil servant and military manpower reductions that caused Navy Program Managers (PM's) to rethink the way weapons test was conducted. They had seen the example set by the Air Force and industry. It was demonstrated that no two integrated test teams could be modeled exactly alike because each program had different driving elements such as: budget, politics, service position, platform maturity, resources, schedule, team personalities and relationships, test location, etc. The Navy began to formulate the foundation for their Integrated Test Team (ITT) concept in February of 1993 when the Navy's V-22 Osprey Program Management team signed-up to performing flight test in an integrated fashion. The ITT concept was outlined in the Engineering and Manufacturing Development (EMD) contract with the prime manufacturer of the aircraft, Bell-Boeing. The rest as they say is history. The Navy's V-22 ITT was established at the Naval Air Warfare Center, Aircraft Division (NAWCAD), Patuxent River Md. The F-18 E/F program was quick to follow at Patuxent River, laying the groundwork for their ITT the following year.

3 RATIONALE BEHIND THE DECISION TO FORM AN ITT

The first attempt at conducting concurrent government and contractor flight test with the MV-22 was during the program's Full Scale Development effort. At that time the

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

contractor and government established a participatory flight test program with the intention of eliminating redundant testing while providing an early opportunity to identify potential deficiencies so that their correction would not adversely impact program schedule or costs. This effort was hampered by numerous contractual restrictions imposed on government participation that essentially relegated the pilots and engineers as monitors of the contractors test operations. Because of the narrow level of government participation they could not meet their developmental test objectives during the participatory testing. Therefore, a full series of dedicated government DT flight test periods was required.

Even so, early government involvement with the contractor did familiarize them with the advanced technology of the V-22 Tiltrotor aircraft. As a result the government was able to identify certain potential design deficiencies early in the prototype development allowing changes to be made. This was at its' best when the cockpit management system was redesigned. As a result of the early experience gained, the government pilots were able to work closely with the contractor to create a "user friendly" cockpit.

Early participation by the government testers allowed this major design change to occur early enough to support the EMD test schedule.

It was early successes such as this that solidified the value of integrated teamwork, and would later anchor the justification to form an ITT.

4 THE V-22 ITT'S CLASH WITH EXISTING TEST PHILOSOPHY

NAWCAD/ITT

Historically, Navy developmental testing was conducted in a closed environment, independent of contractor testing, without taking direction or guidance from either the contractors or Navy program management. As a result, the Navy felt they could always deliver a thorough, factual report that both characterized the weapon system, and that was unbiased by any parochial interest. These tests also provided an initial assessment of the aircraft's potential to conduct the intended mission, as well as, identifying potential deficiencies and enhancing characteristics.

With the ITT concept the Navy consolidated its DT objectives into the contractors flight test program. In a sense, the Navy test community was subjugating its test authority to the contractor and the PM. It was able to do this by being full members of the ITT's management, pilot and engineer structure. Then by working together both the government and contractor defined their DT objectives in a series of detailed test plans which were approved by both parties. Additionally, to ensure Navy DT objectives are fully met prior to OPEVAL a dedicated, Navy only, TECHEVAL was scheduled.

Not everyone in the Navy test community accepted this concept with open arms. Some were wary that the Navy was giving away its role as the "independent assessor"; that government members would become biased to favor contractor objectives, and that inevitably the fleet might acquire an inferior product. The fact that this existed demonstrated the age-old attitude of government mistrust of the prime contractor, with the core assumption that contractor profit motivation always came ahead of product quality (in terms of aircraft mission capability).

GOVERNMENT/CONTRACTOR

Contractor flight test has previously focused on envelope expansion/definition and other testing required to show that the aircraft met the contract specification. On the other hand, the government tests validated that the aircraft met specification (spec compliance) while providing an opinion on whether the weapons system would do the mission. During the previous government development test periods system deficiencies would be identified, and then reported back to the contractor for correction after agreement by the PM.

The ITT is an IPT within a much larger IPT organization that includes design and manufacturing as well as flight test. It is typical for members of the ITT to belong to other IPT's, particularly design teams. Being members of both a test team and a design team changes the role of independent tester to include one that gives the tester some potential ownership in the systems design. As such, a level of bias may be infused into the process. A concern exists that being closely associated with the design precludes an individual from conducting an independent, unbiased evaluation. Additionally, some feel that testers who are part of the design process relinquish part of their T&E role. Yet this early involvement by the tester gives the program manager relief from later deficiency corrections.

NAVAIR/NAWCAD

The Naval Air Systems Command (NAVAIR) has been the developing agency for most Navy aircraft, working closely with the contractors while reviewing the design and management of the development program. When the system was sufficiently developed and there was a need to support a program milestone NAVAIR would task NAWCAD, Patuxent River, to conduct an independent flight test to report on the aircraft's progress.

Since the ITT is now an IPT that is one of many IPT's directly under the leadership of the PM, the flight test team is under the direct leadership of the PM, while also being responsible to NAWCAD for ensuring their processes and responsibilities are fulfilled by the ITT. Again, there is concern by some that a test organization led by the PM loses its ability to conduct independent assessment because it is too close to the design aspects of the program.

5 THE INITIAL V-22 ITT SETUP

POLICY CONFUSION

Initially there was some confusion regarding roles and responsibilities associated with the ITT as written into the EMD contract. An example was with regard to the historical Test Authority (TA) role that Patuxent River normally assumed in accordance with MIL-8708. The Naval Air Systems Command was quick to rectify this confusion by amending 8708 through its specific appendix for the V-22, were they now assumed the TA role. As the acquisition authority, the PM had every right to assume the TA, in fact, in light of the sweeping test reforms to come, their assumption of the TA would prove beneficial; primarily since the contractor was lead of the ITT, with Patuxent River subordinate, the contractor was contractually obligated to take direction from NAVAIR, not Patuxent River, thus some confusion was mitigated in whom the contractor answered to regarding T&E matters.

THE MOA

A memorandum of agreement (MOA) was written which intended to give an upper-level set of guidelines from which the ITT would operate. The parties who wrote, reviewed, and negotiated this document included members of the government test team, the contractor test team, the government chief systems engineer (class desk), and the contractor Joint Program Office. Though eventually the MOA would be used infrequently, and a set of common procedures documents would actually drive the teams actions, the exercise in sitting down and tackling difficult issues while writing the MOA proved to be a critical relationship builder that got the entire evolution rolling. Generating this document required each party to justify their opinion as to the teams functional makeup, and, it required everyone, face-to-face, to truly buy-in to the ITT concept.

THE COMMON PROCEDURES

The team quickly realized that a set of common procedures was needed to govern daily flight test operations. Everything from flight operations procedures to aircraft maintenance to refueling. The reason this was so important is because each party, Bell, Boeing, and Patuxent River each had its own, and different, set of flight test/operating procedures. Three situations quickly emerged:

- the scope of this effort was very large
- negotiating operating agreements was easier said than done
- and, the Defense Logistics Agency (DLA/DPRO) requires a core set of procedures to be in place prior to aircraft delivery to a new operating site.

The final scope of the common procedures would cover over 60 different procedures. Every aspect of ground and flight operations had to be jointly documented to allow for clear, approved guidelines in which to work; this was especially true due to the fact that Bell and Boeing mechanics, engineers, and pilots were working side-by-side, and if a specific operation was not clearly defined, the individual tended to revert to doing the job the way he was trained by his parent organization; depending on the operation, parent organization operations could have been in violation of DLA principle site regulations.

THE SIDE-BY-SIDE PHILOSOPHY

From the beginning, government and contractor managers agreed that the best way to make the ITT concept work was to truly integrate all personnel by physically locating them side-by-side. No one was to be an exception. Pilots, engineers, managers, maintainers would all be collocated. This concept created a real camaraderie between the personnel collocated. Information flowed easier, relationships were built, issues could quickly and easily be discussed, and independent objectives could be shared which heightened each parties understanding of each others job objective. The reliability, maintainability, and supportability, and system safety groups would be the only groups not collocated. The side-by-side arrangement drew criticism by many government development testers in that they felt this concept would further support the creation of biases in the government "independent assessors" eye. It became validated over the years on this team that collocating created no biases either way. The RM&S and system safety groups felt they could not take the chance thus they opted to segregate. It should be noted that Bell-Boeing did collocate their RM&S personnel with good results.

PROPER PERSONALITY PHILOSOPHY

The ITT concept is not something that everyone immediately bought into; some still have not seen the benefits it can and has provided to the acquisition process. The initial architects of the V-22 ITT staffed the team with the highest quality personnel in their fields. It quickly became apparent that a good attitude was as important as technical competence. In many cases, proper education and communication of the reasons and objectives of the ITT concept were able to turn-around a bad attitude, in other cases it was best to make a personnel change. It cannot be stressed enough the importance of staffing personnel who have been educated and understand the ITT concept, and then enter into the concept with the attitude that they are going to strive to understand the other parties objectives, they will not accept failure, they will seek to openly communicate without hidden agendas, they will seek win-win arrangements, and they will attempt to constantly synergize the talents of the entire team.

BEST PERSON FOR THE JOB PHILOSOPHY

Along with the decided philosophy that government and contractor personnel should be collocated to facilitate healthy communications, the other integrated decision was that immaterial of the job, the person best qualified to perform that job would be assigned; government, Bell, or Boeing. This

immediately raised the issue of government liability when government personnel were assigned to do classically contractor development jobs. Liability had to be addressed with regard to flight test decisions that now could be made by government personnel which may effect contractor flight rate and/or data production that schedule and award fee were based on. Bell-Boeing, as well as NAVAIR bought the concept and off we went. Although the team never had a situation where finger pointing occurred, everyone was sensitive to the issue, and it could be argued that significant decisions were always postured for contractor personnel; and, for the most part that was satisfactory at the working level as long as government personnel felt they were adequately included in the decision process. Of course, government management always had the right to make critical decisions where they felt necessary, and Bell-Boeing always listened. The best person for the job philosophy highlighted the need for great team communications. This is because if one party was selected to perform a task that the other party felt they should be performing, as long as planning, analyses and reporting were jointly derived, there were never any hard feelings.

THE ORIGINAL ORGANIZATIONAL CHART

The original ITT organizational chart was classically layered with the contractor on top. Aside from its hierarchical structure, the most obvious item to be noted is the fact that the contractor is in charge. From an organizational chart perspective, one could surmise that contractor personnel have supervisory or influential roles over Navy personnel. The thought here was that in some instances they may, however, when it comes to independently reporting on the performance of the aircraft, Navy personnel only answer to the Navy, and can report without influential bias from the contractor. With that said, every attempt was made to produce integrated test reports where applicable. Some challenged that this was impossible. That a structure of this type again positioned Navy evaluators too close with the contractor to properly evaluate the system. The critics were proven wrong, and here is why. First, it must be recognized that just as contractor personnel are viewed as "over" Navy personnel, senior Navy personnel on the chart are also "over" contractor personnel. The bias had the opportunity to go both ways. However, instead of a bias occurring, opportunities to communicate one anothers objectives were taken advantage of, and each side gained greater appreciation of what the other was doing. This helped to eliminate trivial discrepancies documented by Navy personnel, and it helped the contractor focus on mission essential deficiencies. Additionally, Navy managers committed to focusing on constant leadership and interaction with Navy engineers and technicians to routinely, openly discuss this issue of bias, and thus the team learned to work the issue in their favor, rather than be absorbed by it. The original organization chart, though the basis of the organization, would be reorganized in two years time to reflect an IPT structure more common to the rest of the program.

6 HOW MAINTENANCE WAS CONDUCTED AND QUALITY ASSURANCE WAS REGULATED

Aircraft Maintenance was the contractual responsibility of Bell-Boeing. The Defense Logistics Agency is charged with overseeing the contract. As the V-22 aircraft are government furnished property the contract contains a ground flight risk clause that limits the contractor's fiduciary responsibility in case of damage as a result of an accident. This limit is in effect only if the contractor develops ground and flight operating procedures, approved by DLA (the Government Flight Representative), and conducts their operations in accordance with these procedures.

Although the contractor is responsible for all aspects of the aircraft's maintenance, the GFR provides an independent quality assurance oversight of the contractor's efforts, ensuring that approved processes and procedures have been used.

7 THE BIG CHALLENGES AND THE BIG SOLUTIONS

THE NO WIN SITUATION REGARDING FLIGHT PRODUCTIVITY

The V-22 ITT became stuck in a no win situation regarding flight productivity. And because of the organization, Navy test management was held just as responsible as the contractor. This situation posed a challenge to Navy test personnel: allow the contractor to take the heat and plead the fact that they're in charge; or, take the opportunity to recommend new methods and processes for maintenance, reporting, and scheduling. The reason this situation was no win is because: 1) the aircraft was an aging airframe that was being put through the wringers in flight, new problems and unscheduled maintenance were routine events, 2) maintenance and engineering personnel were working to a decreasing budget and there never seemed to be enough people to get the jobs done, and 3) there were constant requests for new data that caused redirection and rescheduling to occur, thus a loss of efficiency ensued. At the same time, while challenged to rise to the situation and devise innovative ways to keep flight productivity high, the team had to keep safety in the forefront, standards and processes could not be altered or minimized if anyone thought safety might slip. Thus as more and more had to be done, where safety could not be compromised, where the aircraft was continually suffering from unscheduled maintenance, and where plans and schedules were routinely redirected, it should not have been a mystery why we could not maintain 15 flight hours per month. The solution was to communicate as often as possible with headquarters regarding the impact of redirection and unscheduled maintenance. Nothing could be hidden, no information delayed, and everything had to be documented.

Dr. Deming, the total quality guru, uses a "red bead" experiment to illustrate that workers are victims of the system in which they work. He uses the exercise to illustrate the helplessness of workers to meet productivity objectives when

the system is statistically incapable of achieving such results. The outcomes, and consequently the workers, are at the mercy of chance. In establishing the productivity criteria in an ITT, all parties must understand the statistical capability of the system they are testing to achieve results.

FINDING EACH OTHERS TRUE OBJECTIVES

Despite what each side thought, neither one of us at the onset truly understood the others objectives on the team. Personnel turnover made this a constant battle, because the new person had be reeducated, a process that took months. It took perseverance to continually remind each side why the other was there, and why their job was meaningful. The key here was to be upfront. As soon as a situation arose, at any level, where it was obvious one side had disdain for the other's presence or input, it had to dealt with immediately and openly, otherwise it became cancerous.

THE ORGANIZATIONAL EVOLUTION

The 3-Organization Problem (ITT, JPO, NAST):

A significant issue with regard to the organizational development of the ITT was that there were numerous perspectives on the ITT's organization. NAWCAD Patuxent River recognized one set of leadership, the ITT itself recognized another, the Bell-Boeing JPO yet another, and NAVAIR headquarters another still. This created confusion and misdirection at all levels within the ITT which required a constant effort to mitigate.

Who Works For Who

The classical outcome of this organizational confusion was that people were constantly either asking themselves "who do I work for?", or, they were complaining that they had so many bosses they could not get their job done efficiently. The proper answer should have been, independent of the organization model in place, I must work for the customer - that being the Program Manager and the Fleet user. If this approach were taken, organizational misalignment would only have been manifest in the teams internal communications and productivity; if that is the fact, process reengineering can be focused inward with relative ease. If no one knows who to answer to, a lack of team productivity becomes a finger pointing affair. It is recommended to establish an ITT with an organization and agreed upon levels of responsibility and empowerment upfront prior to startup.

Transition to IPT's Within The ITT

In order to help this situation the V-22 ITT underwent an effort to reorganize in an IPT structure. This was seen as good timing since the rest of Bell-Boeing was already IPT organized, and the NAVAIR PMA organization was rewriting their Program Operating Guide with an IPT reorganization flavor.

The Organizational Chart Development

The ITT's organizational structure, as previously mentioned progressed from a classical hierarchical "stovepipe" structure to a more IPT oriented structure. The greatest issue here was not only the fact that the majority of the organization was not fully briefed on the exact roles and responsibilities of those seen to be in leadership positions, but more so, that no one in the organization remained focused on the importance of communicating the teams organization to the front line, nor was there significant communication to NAVAIR of the need to alter the organization. A reason for this was that the ITT's management was so busy managing to remain productive, and budgets were always so tight, that no one ever took the time to truly lead, that is, to focus on the future, to stress communications to the team and to the customer, or to work hard at clearly defining roles and responsibilities.

THE BIG SUCCESSES

The Flight Test Review Board

The Flight Test Review Board (FTRB) was a major success for both the government and the contractor. The premise behind the FTRB was to reduce, or possibly eliminate the need for deficiency reports (which in reality are unaffordable quality reports because they are written too late in the acquisition process), thus inserting government identified deficiencies as early as possible for timely correction; and, to insert the government in the correction process to aid in creating an environment where the government DT personnel would not feel as if the contractor was avoiding mission essential deficiencies. The board was comprised of contractor and government personnel alike, chaired by the contractor. The lead government DT representative did have the right to defer any deficiency pending further data from the contractor regarding correction. Any team member could author a FTRB "squawk". As squawks were written copies were provided to pertinent government and contractor ITT members, then compiled to submit to the board for review. At the board all squawks are reviewed and defended by the author to ensure adequate justification existed, if so, the squawks are handed to Bell-Boeing representatives to bring back to the company's for correction and/or disposition. At the board the previous months submitted squawks are dispositioned by the company representatives. The ITT can accept the disposition and close out the squawk, or they can be rejected or deferred. This process truly brought all players into the deficiency identification and correction process. It eliminated frivolous deficiencies which were without proper justification, it identified legitimate deficiencies early for more economical correction, and it aided the probability that "mission critical" deficiencies as viewed by development testers were being corrected, or at least addressed, such that the probability of passing Operational Test was increased.

The Teamwork and The People

The FTRB, the side-by-side seating arrangement, the push for productivity, the long hours, the weekends, the dependence on each other because resources were short, and the underlying attitude that we were both in this together, that the success of the ITT was dependent on government and contractor alike, and that both sides would be held accountable for any failures, truly created a combined sense of teamwork. Teamwork is critical for an ITT, and teamwork is dependent on attitude. Sometimes no matter how hard you try a bad attitude will be present. An ITT setup cannot afford even one bad attitude. A bad attitude with regard to mistrust or dislike for the other entity can not be tolerated, especially among management. A key factor in designing a successful ITT is staffing the team with people who are devoted to making it work at any cost, are willing to constantly look for win-win situations, and are not hesitant on replacing personnel who cannot work within an "ITT" attitude.

8 ITT INVOLVEMENT WITH THE OT COMMUNITY

OPERATIONAL ASSESSMENTS

OT-IIA and OT-IIB were early operational assessments to evaluate the V-22 aircraft's potential operational effectiveness and operational suitability. Because of the extremely limited availability of the prototype test assets and a tight program schedule these evaluations were conducted with a joint DT/OT flight crew. As such, each organization's roles and responsibilities were defined early in the planning process and were formalized in a Memorandum of Agreement. The DT organization was responsible for the safe operation of the test aircraft while the OT organization was responsible for developing operationally representative missions. Although these were narrow scope evaluations they successfully demonstrated that at times the OT and DT communities working closely make effective use of limited assets.
An additional benefit of the operational testers working closely with the developers is that the developers get to see first hand the issues, concerns and problems with the weapons system. This not only gives the engineers an early start at correcting deficiencies, but it also gives them a better understanding of how to correct the problem.

INTEGRATED MAINTENANCE TEAM

The next logical step in integrated testing is to integrate the maintenance. An effort is underway to assign members of the operational test community to the contractor's maintenance team for EMD. Several advantages of early involvement in the aircraft maintenance are: an early look at the training that will be required for the fleet maintainers, and understanding of the complexity of the aircraft's maintenance, and, an early look at the maintenance publications and supporting documents. During EMD the contractor will be responsible for the aircraft's maintenance, so integrating government maintenance personnel will require a detailed MOA that ensures each party can accomplish its goals.

TOTAL INTEGRATED DT/OT CONCEPT

During EMD an integrated DT/OT effort is planned. This means that the OT personnel will form a detachment to work closely with the DT personnel. The pilots will be allowed to participate as copilots during low risk developmental flights and will be encouraged to participate in the DT deficiency reporting and correcting process. This early involvement by OT personnel is intended to increase their familiarity with the V-22's advanced technology while helping the developers identify and correct deficiencies as early in the program as possible. Even with the operational testers participating in DT they will still conduct an independent OT-IID and OPEVAL. It is expected that the familiarity they gained during DT participation will reduce proficiency flying prior to their dedicated operational test periods, thus allowing them to make more effective use of their test time.

9 CONCLUSIONS: SYNOPSES OF ITT LESSONS LEARNED

ORGANIZATIONAL

A clear team organization model must be established in advance, and approved by higher management (customer). If working in an AIT/IPT organization, charters and mapping must also be performed upfront.

ITT success is greatly a function of personality, from management to the front line of the organization chart - ITT's will only work if the people want them to.

Strong leadership is critical. Team leadership should be viewed as complementary between the government and contractor leaders.

Contractor union issues did not seem to be a factor regarding team formation. However, union employees did tend to "walk off" the job when differences arose, and the government had no jurisdiction over union personnel/policy.

Government technical engineers across the board do not match one-to-one with contractor engineers; proper disciplines are not always present for "side-by-side" integrated seating arrangements.

Proper ITT setup and working relations require clearly defined roles, tasks, responsibilities, and objectives; this initiative must come from upper management. Without this clear definition, confusion ensues regarding who engineers are responsible to (NAWC, ITT, NAVAIR, B-B, Competencies, Squadrons); under confusion people tend to respond to inputs from their parent organization, vice the ITT, creating a cyclic effect that continues to worsen.

DT and OT objectives can be accomplished through an ITT setup (OT involvement requires significant work, especially in the area of personality/philosophy acceptance of an ITT

approach); combined DT/OT saves schedule time, and improves efficiency of testing (nonserialized tests).

Responsibilities should be distributed between contractor and government based on experience, but not necessarily based on seniority of experience.

Do not be afraid to try different things within the ITT. Encourage people to speak up if they see a better way of doing things, and then implement, learn, and reengineer if necessary; in this regard ITT's can break barriers that tend to halt such idea implementation.

Parent organizations must empower the personnel in an ITT, if they do not, greater barriers can be built, and team effectiveness can be mired in the "infinite-boss" syndrome, and the effect of constant miscommuniques requiring redundancy of work and "backtrack damage control" becomes commonplace.

PROCESSES

Government and contractor test philosophies must be communicated and understood between parties upfront so that flexibility and processes may be built in early.

Common operating procedures must be completed well prior to standup of the ITT in order to identify the bounds of operating instructions and regulations, and to provide the required guidance to all parties (especially those working maintenance and flight operations).

Common operating procedures are a must when working with different corporate philosophies. This results in the development of a "best of" procedure which provides a more effective and efficient procedure.

The ITT did not originally account for extraneous regulations required to be satisfied with respect to operating procedures (ie DLA - DLAM 8210). Always make sure all regulatory agencies are understood and accounted for early.

A common deficiency process (FTRB replacing the Yellow Sheet method) proved to be exceptional. The result was a streamlining of government corrective action on identified deficiencies (there was no "backburnering" of government deficiencies, all deficiencies became ITT).

TEST CONDUCT

Test Plans <u>can</u> be written jointly. Safety Checklists are value added.

Test conduct and reporting <u>can</u> be performed jointly with a measurable time savings; this supports government and contractor view points.

You can never spend enough time planning for a test, and, the government-contractor ITT planning approach tends to give more thought to the process in a set time as compared to just one group doing it alone. Additionally, ITT management must agree early-on to timeline /schedule allocation (deadlines) for test planning.

Effectively merged contractor-government test plan philosophies have resulted in an improved test plan.

ITT schedules tend to be 16-24 hour-a-day operations, 6-7 days per week, with different contractor-government vacation schedules. Government setup does not always support this tempo of operation, and government management cannot incentivize their people to work these hours the way the contractor can - this fact can lead to conflict. (ie, base closure, govt. limit on OT rates, range shutdowns, safety standdowns, etc.).

LOGISTICS

Warehouse and spares inventory must be established early. The warehouse must be fully stocked and totally supported by the parent suppliers (ie minimize counter-to-counter shipping on request). The site should be stocked with both aircraft and test support parts/spares.

A dedicated aircraft shuttle between key sites can help tremendously.

Typical military maintenance departments (AIMD's) do not seem to be able to support a contractor aircraft developmental schedule.

OVERALL

An ITT increases government awareness technically, programmatically, and managerially of contractor developmental issues.

Government engineers proved to be as capable technically as contractor personnel in leading the conduct of tests, and interfacing between contractor and government agencies.

An ITT concept allows government involvement in "classical" contractor developmental testing (on the spot deficiency identification and involvement in redesign/fix effort) rather than after prime development (critical design review) is in essence completed.

ITT's can, and ought, to be different. (ie, nothing says the V-22 organization chart should look like the F-18E/F ITT organization chart. Each team has different nuances that should drive different ways of doing business.

At first, the contractor complained at the limitations of the Navy base infrastructure (i.e. restricted takeoff direction, waiting on fuel, etc.); however, good things eventually came out of such restrictions in that the team was required to formulate new (and improved) procedures to deal with such limits, which in the end increased productivity; and, it also

allowed for the aircraft to have to operate in more diverse conditions (crosswinds) that would not have otherwise come to identify a critical problem (pitch-up with sideslip in crosswind takeoff).

Single site ITT's should be setup for long-range commitments if that makes sense (i.e. analyze the time requirement carefully). Single site ITT's may not be suited for short term (<1-2 years) projects requiring high maintenance/modification of aircraft. If an ITT is setup for a short-term project, team infrastructure should be tailored to suit (i.e. total spares stock may not be required). A great hindrance to productivity can occur when a team is setup with a short-term scope in mind, and then after a couple years it is decided to extend the effort.

ITT setups give the contractor a greater operational (mission) understanding which tends to influence the designer for the better.

The ITT setup facilitates improved OT participation and relationships, even government-to-government.

Upfront costs to establish an ITT are high (procedures development, infrastructure, personnel moves, etc.), but preliminary analyses show that the investment pays for itself in the long-run through a decrease in test time required (product to customer quicker), and a decrease in program risk. Some pure financial analyses show the ITT benefit as break even at best as compared to conventional acquisition testing.

Personnel compensation (EDP's, OT, travel, fringes) must be established upfront, and at best agreed upon by the majority of line workers, in order to minimize personnel disruption.

Ensure time is planned to account for the training of new personnel relocating (ie contractor maintenance personnel require AIMD training on yellow gear, hazmat, etc.).

Prepare an Environmental Assessment (EA) for test early. Communicate early-on with the proper environmental agencies.

Host tenant support agreement (HTSA) negotiations should be completed as early as possible, then ensure routine reviews are scheduled to cutoff potential future conflicts.

10 ITT's ROLE IN THE ACQUISITION STREAMLINING INITIATIVE

The ITT can be seen as playing a major role in DOD acquisition streamlining initiatives. Elimination of classical T&E redundancies between contractor and government is only the first step, and an FTRB setup which inserts deficiencies for correction as early in the design process as possible is a good second step. The total combination of DT, OT, and contractor development flight test takes you one step farther. And the most efficient situation, requiring the greatest trust among parties, is to allow the contractor to develop its product with only pinpointed DT/OT representatives, much like in the development of a commercial airliner.

11 COST ANALYSES

It is hard to acquire metrics to conduct a cost comparison analyses between an ITT and conventional "serial" testing. This is partly because little accurate past data exists on the true cost of a conventional flight test program. Even if it did, it is hard to "non-dimensionalize" two different programs. Additionally, an ITT produces savings through intangible efforts (teamwork, synergy, shared data, etc.) that are nearly impossible to measure. Looking at an ITT that is well run, it is hard to believe that it would be less economical than past classical methods.

12 TIME-TO-TEST ANALYSES

There can be no argument that an ITT setup shortens time-to-test. The combination of government DT events with contractor DT events is obvious. The deficiency reporting method which corrects the design on the fly, so to speak, saves significant time. And teamwork aspects that give government test personnel advanced insight into system performance can eliminate the need, or reduce the scope, of certain tests.

13 ACKNOWLEDGEMENT

The V-22 ITT concept was a bold move, and the personnel from the V-22 PMA who initiative this effort should be recognized: Col. James Shaeffer (USMC, Ret.) V-22 PMA, Mr. Ray Schleicher V-22 PMA, CDR Gary Thompson (USN, Ret.) V-22 DepPMA, Capt. Tom Curtis V-22 Class Desk, and Mr. Dave St. Jean V-22 Class Desk.

Additionally, the early days of the ITT setup where especially laborious. Key personnel associated with the initial development of the ITT were Mr. Sam Porter (NAWCAD), Col. Paul Martin (NAWCAD), Mr. Roger Marr (Bell Helicopter), and Mr. Phil Dunford (Boeing Helicopter).

A special thank you is offered to the many men and women who served, and still serve, in the V-22 ITT. Their many hours of work will never be forgotten and will always be appreciated.

14 REFERENCES

1. Frank N. Lucero ,THE USAF COMBINED TEST FORCE (CTF) CONCEPT, undated.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-593	ISBN 92-836-0050-9	UNCLASSIFIED/ UNLIMITED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly-sur-Seine, France

6. Title
Advances in Flight Testing

7. Presented at/sponsored by
The Flight Vehicle Integration Panel Symposium held in Lisbon, Portugal, 23-26 September 1996.

8. Author(s)/Editor(s)	9. Date
Multiple	December 1997

10. Author's/Editor's Address	11. Pages
Multiple	400

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other AGARD unclassified publications is given on the back cover.

13. Keywords/Descriptors

Flight tests
Aircraft
Avionics
Software development
Reviews
Integrated systems
Test facilities
Flight control
Flight simulation
Military aircraft
Global positioning system
Air navigation
Aviation safety
Performance evaluation
Management

14. Abstract

The Symposium comprised six sessions, each being devoted to a particular field, with one session on Systems Evaluation, including avionics, navigation, propulsion and weapons aspects, two sessions on Technological Advances covering all technical fields such as avionics software, simulation, instrumentation, aerodynamics, test methods etc., one session devoted to an Overview of Current Programmes, one session on Flight Dynamics, incorporating handling qualities, performance and flight controls, and one session addressing Management Problems in Testing. The symposium closed with a discussion between government representatives and manufacturers on "The role of governments in development testing in the 21st century".

Copies of papers presented at the Flight Vehicle Integration Panel Symposium held in Lisbon, Portugal, 23-26 September 1996.

AGARD

NATO OTAN

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Télécopie 0(1)55.61.22.99 • Télex 610 176

DIFFUSION DES PUBLICATIONS

AGARD NON CLASSIFIEES

L'AGARD détient un stock limité de certaines de ses publications récentes. Celles-ci pourront éventuellement être obtenus sous forme de copie papier. Pour de plus amples renseignements concernant l'achat de ces ouvrages, adressez-vous à l'AGARD par lettre ou par télécopie à l'adresse indiquée ci-dessus. *Veuillez ne pas téléphoner.*

Des exemplaires supplémentaires peuvent parfois être obtenus auprès des centres de diffusion nationaux indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de l'AGARD, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus sur la liste d'envoi de l'un de ces centres.

Les publications de l'AGARD sont en vente auprès des agences de vente indiquées ci-dessous, sous forme de photocopie ou de microfiche. Certains originaux peuvent également être obtenus auprès de CASI.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

BELGIQUE
Coordonnateur AGARD-VSL
Etat-major de la Force aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Directeur - Gestion de l'information
(Recherche et développement) - DRDGI 3
Ministère de la Défense nationale
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
INTA (AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

ETATS-UNIS
NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934

FRANCE
O.N.E.R.A. (Direction)
29, Avenue de la Division Leclerc
92322 Châtillon Cedex

GRECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PAYS-BAS
Netherlands Delegation to AGARD
National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM Amsterdam

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
2700 Amadora

ROYAUME-UNI
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar-Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
Etats-Unis

The British Library Document Supply Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume-Uni

Les demandes de microfiches ou de photocopies de documents AGARD (y compris les demandes faites auprès du CASI) doivent comporter la dénomination AGARD, ainsi que le numéro de série d'AGARD (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Veuiller noter qu'il y a lieu de spécifier AGARD-R-nnn et AGARD-AR-nnn lors de la commande des rapports AGARD et des rapports consultatifs AGARD respectivement. Des références bibliographiques complètes ainsi que des résumés des publications AGARD figurent dans les journaux suivants:

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
Etats-Unis

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
Etats-Unis
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

Imprimé par le Groupe Communication Canada Inc.
(membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada K1A 0S7

AGARD

NATO OTAN

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Telefax 0(1)55.61.22.99 • Telex 610 176

DISTRIBUTION OF UNCLASSIFIED

AGARD PUBLICATIONS

AGARD holds limited quantities of some of its recent publications, and these may be available for purchase in hard copy form. For more information, write or send a telefax to the address given above. *Please do not telephone.*

Further copies are sometimes available from the National Distribution Centres listed below. If you wish to receive all AGARD publications, or just those relating to one or more specific AGARD Panels, they may be willing to include you (or your organisation) in their distribution.

AGARD publications may be purchased from the Sales Agencies listed below, in photocopy or microfiche form. Original copies of some publications may be available from CASI.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD — VSL
Etat-major de la Force aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Director Research & Development
Information Management - DRDIM 3
Dept of National Defence
Ottawa, Ontario K1A 0K2

DENMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92322 Châtillon Cedex

GERMANY
Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

GREECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 90502
1006 BM Amsterdam

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
2700 Amadora

SPAIN
INTA (AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

TURKEY
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar-Ankara

UNITED KINGDOM
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES
NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
United States

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
United Kingdom

Requests for microfiches or photocopies of AGARD documents (including requests to CASI) should include the word 'AGARD' and the AGARD serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Note that AGARD Reports and Advisory Reports should be specified as AGARD-R-nnn and AGARD-AR-nnn, respectively. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform resource locator:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
United States

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 22161
United States
(also available online in the NTIS Bibliographic Database or on CD-ROM)

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

ISBN 92-836-0050-9